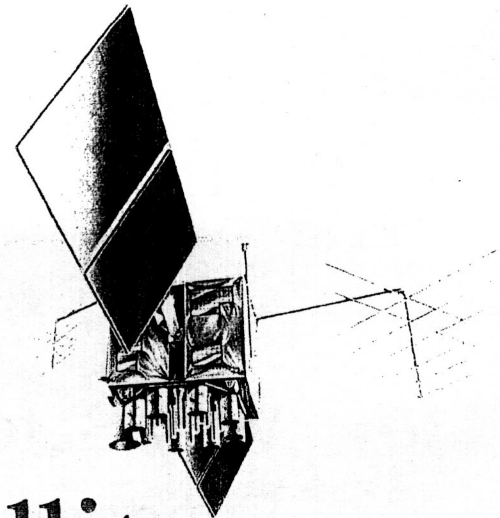
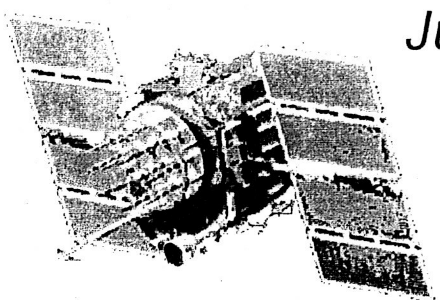


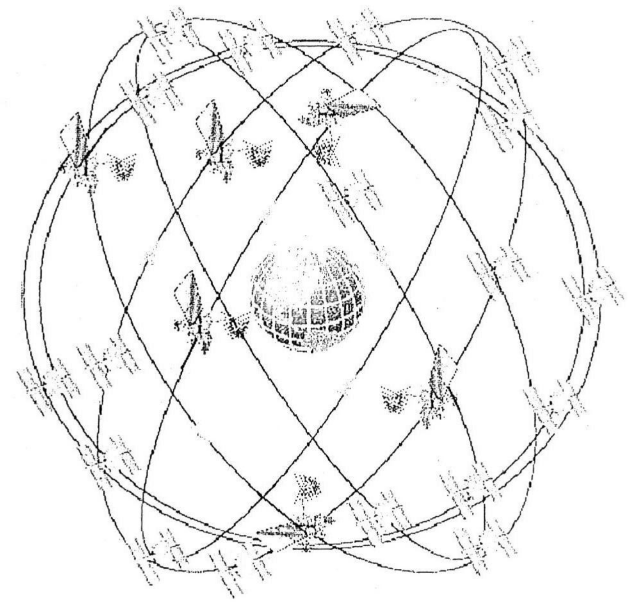
Introduction to Global Navigation Satellite Systems

Michael C. Moreau, Ph.D.
NASA Goddard Space Flight Center

30th Annual Time and Frequency Metrology Seminar
June 9, 2005



Outline



- Why Satellite Navigation?
- Fundamentals of Satellite Navigation
- How GPS Works
- Overview and Status of Global Positioning System:
  - Current GPS
  - GPS Modernization and Future
- Overview and Status of Other GNSS Systems:
  - GLONASS
  - GALILEO
  - QZSS
- Satellite based time transfer techniques

Why is Satellite Navigation of Interest in the Time and Frequency Community?

- GPS has become a primary system for distributing time and frequency globally
- Applications range from use in telecommunications networks to timing laboratories
- Allows users to synchronize clocks and calibrate and control oscillators in any location with access to a GPS antenna

Precise Timing is Fundamental to Satellite Navigation

- Typical receiver provides user position accurate to a few meters by measuring the range (signal delay) to multiple satellites
- Assume the maximum acceptable ranging error contribution from satellite clock is 1 meter:
  - One-meter ranging error is equivalent to 3.3 ns (one meter / speed of light = 3.3×10^{-9} s)
- Clock error must be maintained below this level over 12 hour period (time between satellite uploads)
  - Requires a clock with about one part in 10^{13} stability; (3.3×10^{-9} s / 43200 s = 0.8×10^{-13})

Atomic Clocks in Space

- GPS satellites carry redundant rubidium or cesium oscillators (or a combination)
  - Precise frequency standard provide a reference for generating the ranging signals transmitted by the satellites
- Clocks on the satellites are steered by DoD ground stations to Coordinated Universal Time (UTC) as maintained by the US Naval Observatory (USNO)
  - By mutual agreement, UTC(USNO) and UTC(NIST) are maintained within 100ns (and frequency offset $<1 \times 10^{-13}$)
- GPS provides a link to the UTC time scale

Relativistic Effects in GPS

Atomic clocks in GPS satellites are given a fixed fractional frequency offset of -4.4645×10^{-10} to compensate for relativistic effects in the GPS satellite orbits

- Second-order Doppler shift – a clock moving in an inertial frame runs slower than a clock at rest.
- Gravitational frequency shift – a clock at rest in a lower gravitational potential runs slower than a clock at rest in a higher gravitational potential

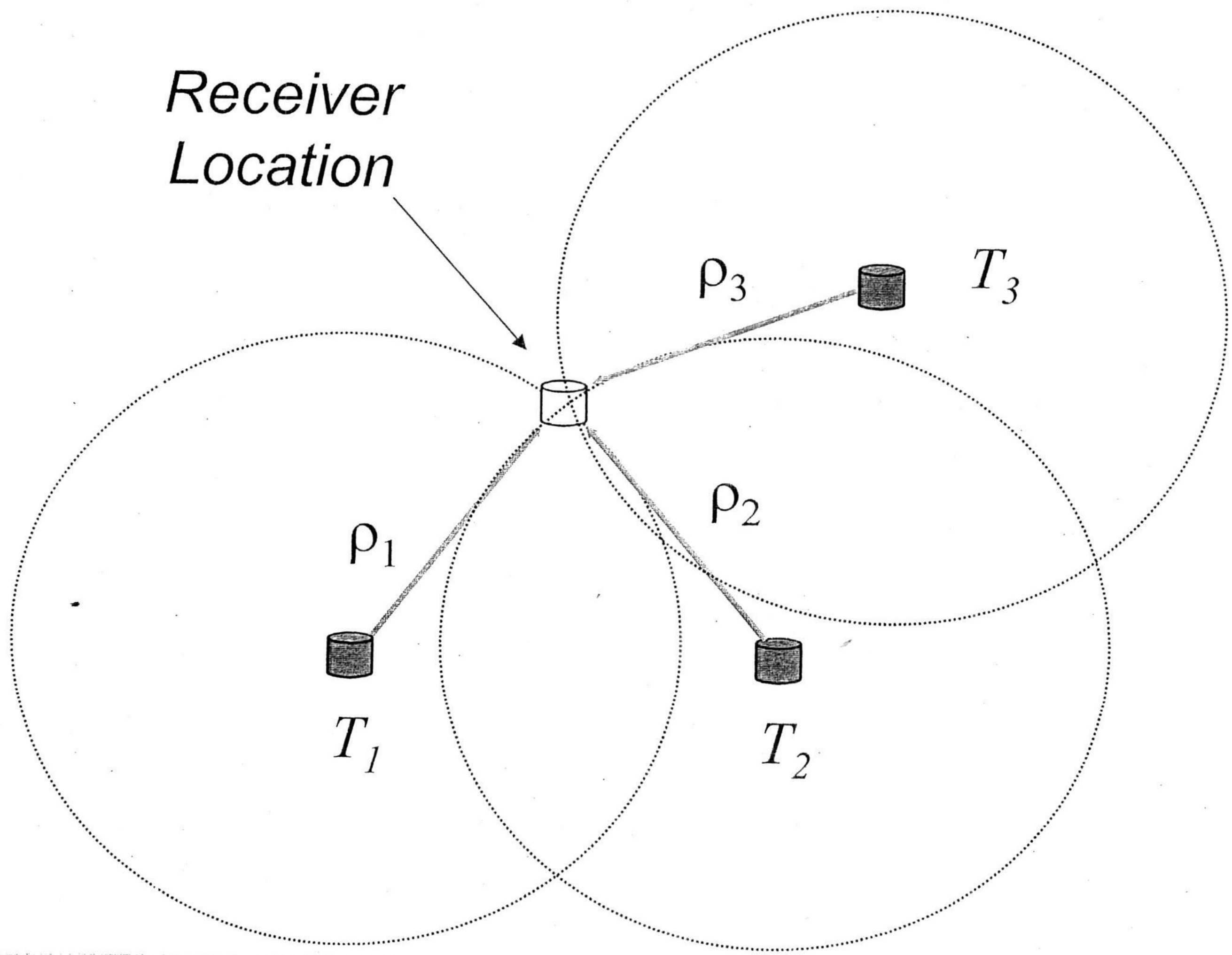
Without this offset, GPS satellite clocks would gain ~38 microseconds per day relative to clocks on the ground.

GPS receivers apply an additional correction of up to 23 ns (6 meters) to account for any eccentricity in the satellites orbit

Fundamentals of Satellite Navigation

- Satellite based navigation is fundamentally based on:
  - The precise measurement of time
  - The constancy of the speed of light
- GPS and other systems use the concept of trilateration:
  - Satellite (transmitter) positions are known
  - Receiver position is unknown
  - Satellite-to-receiver range measurements are used to estimate position

Trilateration Example:
3 Transmitters, 1 Receiver



Position Solution

- The position solution involves an equation with four unknowns:
  - Receiver position (x, y, z)
  - Receiver clock correction
    - Position accuracy of ~1 m implies knowledge of the receiver clock to within ~3 ns
- Requires simultaneous measurements from four satellites
  - The receiver makes a range measurement to the satellite by measuring the signal propagation delay
  - A data message modulated on the ranging signal provides the precise location of the satellite and corrections for the satellite clock

Measurement Equation

GPS receiver measures "Pseudorange" by measuring the transit time of the signal:

$$\rho_k = c\left(t_r - t_T\right)$$

time of signal reception, (based on receiver clock, can be significantly in error)

time of transmission, encoded in signal by GPS satellite clock (known precisely)

Measurement Equation (cont)

- Measured pseudorange to a satellite, k is comprised of:

$$\rho_k = \left\|\mathbf{r_k} - \mathbf{r}\right\| + c\left[\delta t - \delta t_k\right] + I_k + T_k + \varepsilon_k$$

  - true range r_k (known)
  - receiver clock error
  - satellite clock error (known)
  - ionosphere and troposphere delays (estimated or measured)
  - other errors (satellite ephemeris and clock mis-modeling, measurement errors, multipath, receiver noise)

Solution Accuracy

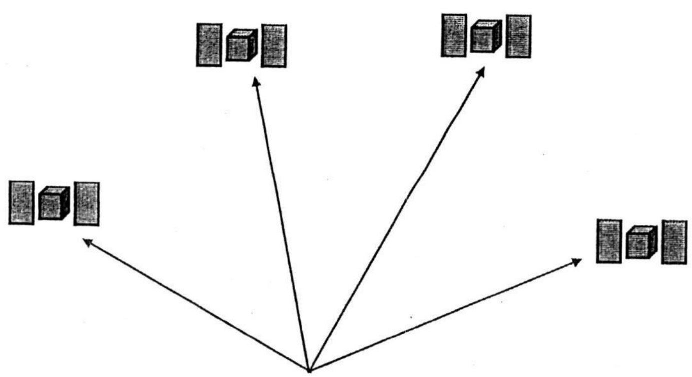
- Two primary factors affect the fundamental position and time accuracy possible from the system:
  - Ranging error – a function of the quality of the broadcast signal and data
  - Geometry – the distribution of satellites in the sky
- The actual positioning accuracy achieved depends on many other factors:
  - The design of the receiver (receiver/antenna noise levels, modeling errors, etc.)
  - Environmental effects such as ionosphere and troposphere signal delays, field of view obstructions, multipath signals, and jamming/interference.

Ranging Error

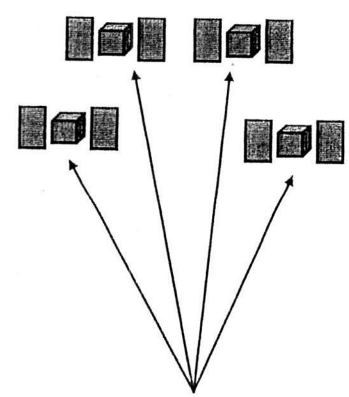
- User Equivalent Range Error (UERE)
  - A measure of the accuracy of the pseudorange along the line-of-sight direction from a particular satellite to the user
  - Indication of signal quality
- Composite of several factors
  - stability of particular satellite's clock
  - predictability of the satellite's orbit

Geometry – Dilution of Precision

- Geometric Dilution of Precision (GDOP) is a measure of the quality of the receiver-to-GPS satellite range geometry
  - Related DOPs exist for position, horizontal, vertical, and time dilutions of precision
- Used in conjunction with the UERE to forecast navigation and timing performance, weight measurements
- For GPS, DOP can range from 1 to infinity, with values in the 2-3 range being typical



Good GDOP



Poor GDOP

Typical Error Budget (Based on GPS)

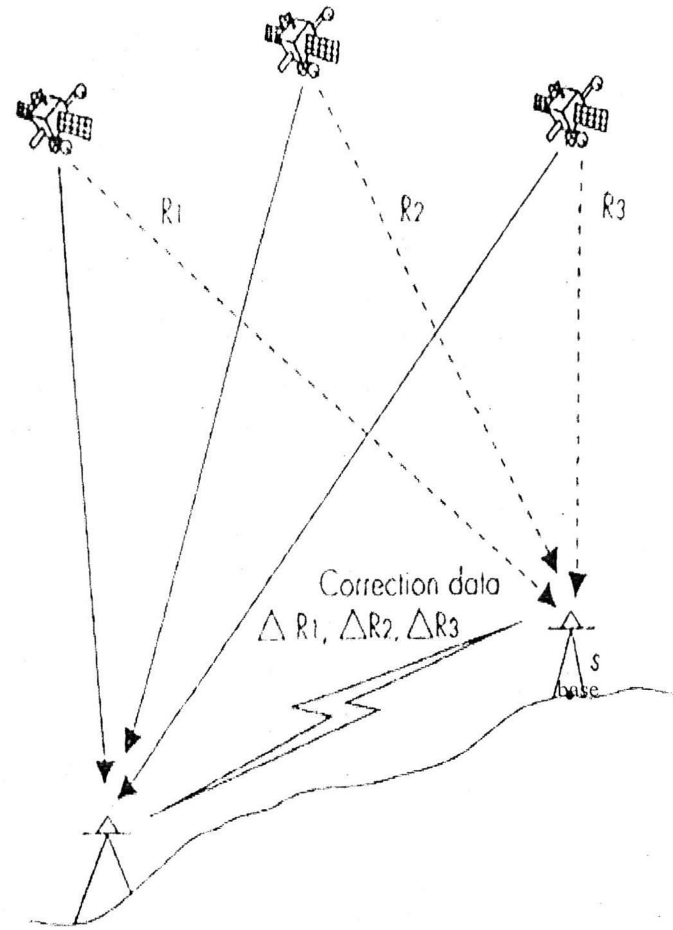
Error Source	Typical Error
Ionosphere (< 1000 km)	1-5 m (single frequency, using broadcast model)
Troposphere (< 20 km)	0.1-1 m
GPS orbits	2.0 m (RMS)
GPS clocks	2.0 m (RMS)
Multi-Path (“clean” environment)	0.5-1 m code 0.5-1 cm carrier
Receiver Noise	0.25-0.5 (RMS) m code 1-2 mm (RMS) carrier

Differential Techniques

Receivers in close proximity can have their common error sources cancel
- Ionosphere and troposphere delays
- Satellite orbit error
- Satellite clock error

Differential approaches
- Broadcast corrections from a base station at a known location
- Difference the data

Relative GPS
- No fixed base station

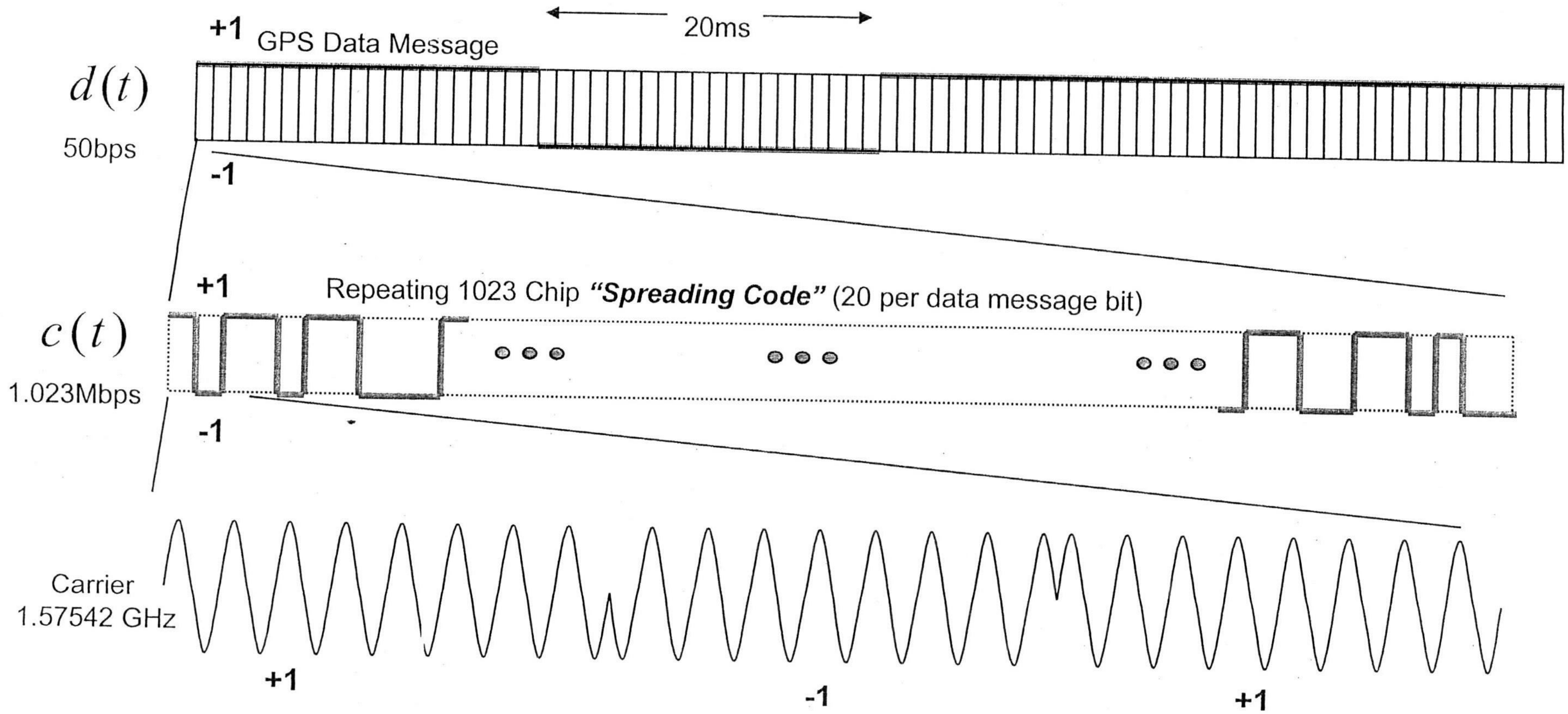


How Does Satellite Ranging Work? Example: Global Positioning System (GPS)

- GPS is an example of a spread spectrum communications system
  - Uses Code Division Multiple Access (CDMA):
    - Each satellite is assigned unique Pseudo-Random Noise (PRN) Code
    - All satellites transmit at the same frequency
  - The power associated with the transmitted data is "spread" over a wide frequency band
  - The received power is very low (below ambient noise levels)
- The transmitted signal is the combination of three signals:
  - L-band carrier signal
  - PRN code
  - 50 Hz data message

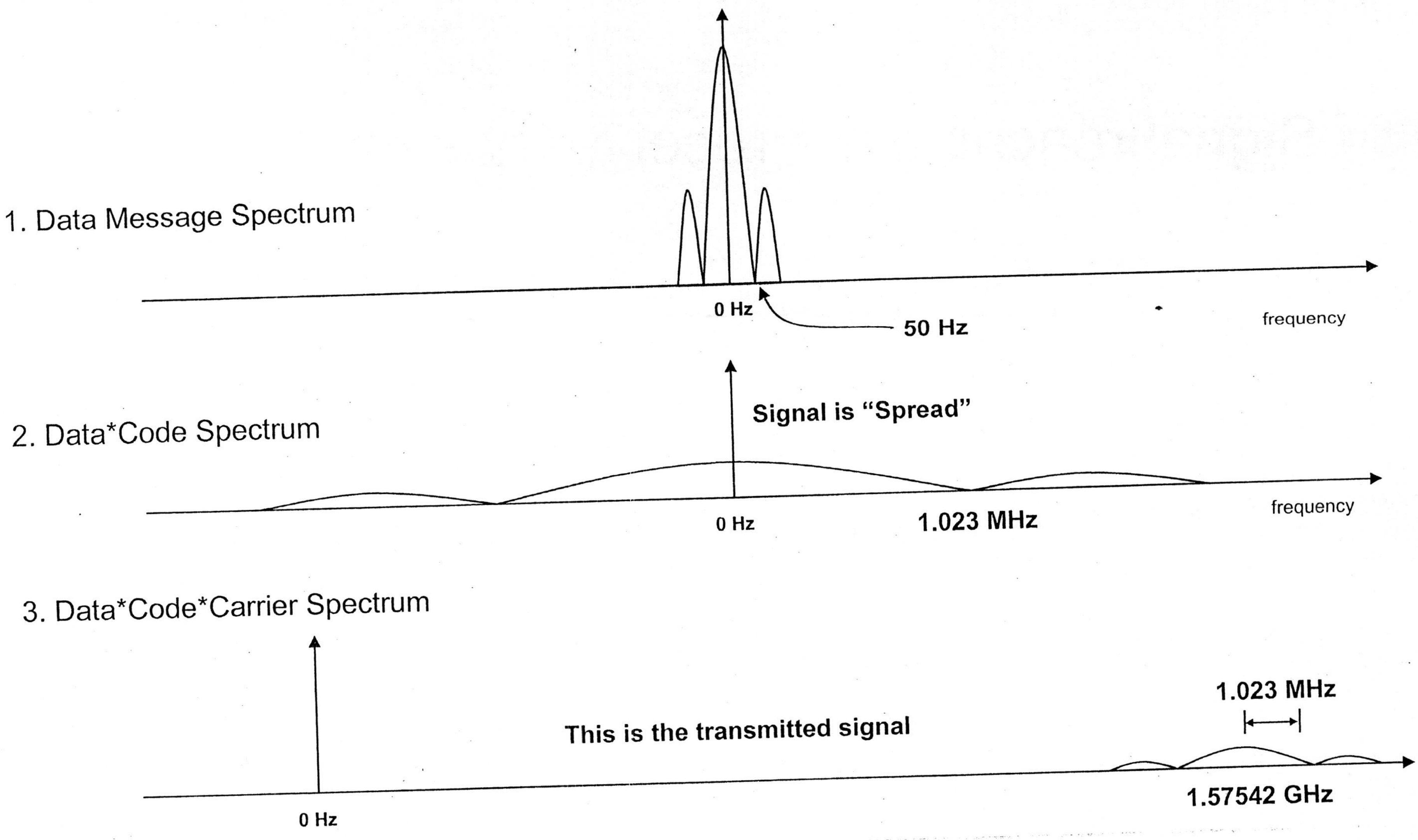
$$y(t) = A \cdot d(t) \cdot c(t) \cdot \cos[(\omega_{L1})(t) + \theta]$$

GPS L1 C/A Signal (Time-Domain)



$$y(t) = A \cdot d(t) \cdot c(t) \cdot \cos[\,\omega_{L1} t + \theta\,]$$

GPS L1 C/A Signal (Frequency Domain)



How Does GPS Work?

- Signal reaching the receiver has three changes:

$$y_{\text{Received}}(t) = A \cdot d(t-\tau) \cdot c(t-\tau) \cdot \cos[(\omega_{L1} + \omega_d)(t-\tau) + \theta] + n$$

  - Time-delay, τ
  - Doppler frequency shift, ω_d
  - Wideband noise, n

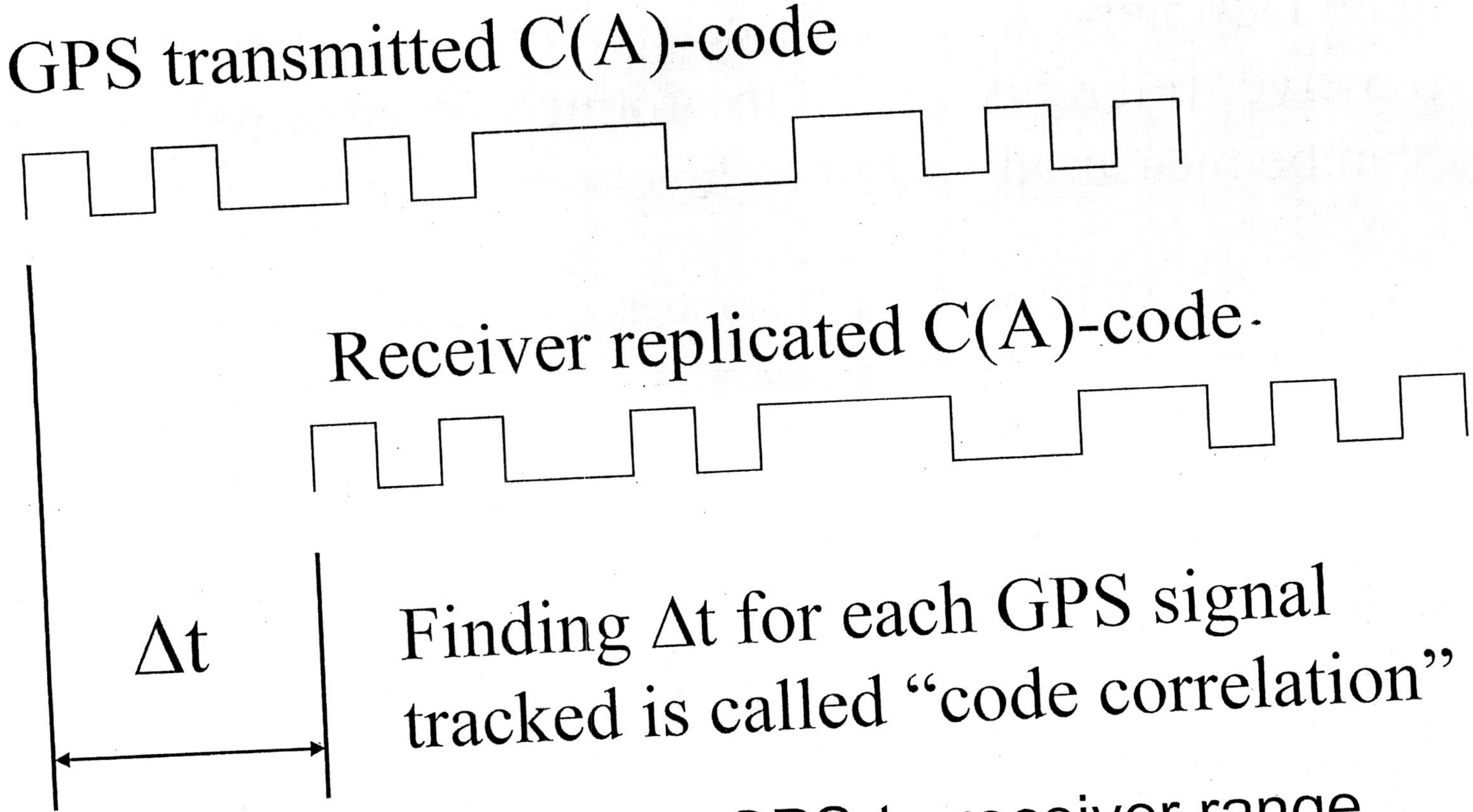
How Does GPS Work?

- In order to detect the GPS signal and recover the navigation data, the receiver must produce a replica of the GPS signal with the correct time delay and Doppler to mix with the incoming signal
  - PRN codes are known
- GPS measurements are derived from the values of the PRN code phase and carrier Doppler shift necessary to produce a large correlation with the incoming signal

GPS Observables

- **GPS receivers typically output 3 fundamental observables**
  - Pseudorange
  - Doppler
  - Carrier Phase
    - Carrier measurement is 1000 times more precise than the code/pseudorange, but has an integer ambiguity

Pseudorange

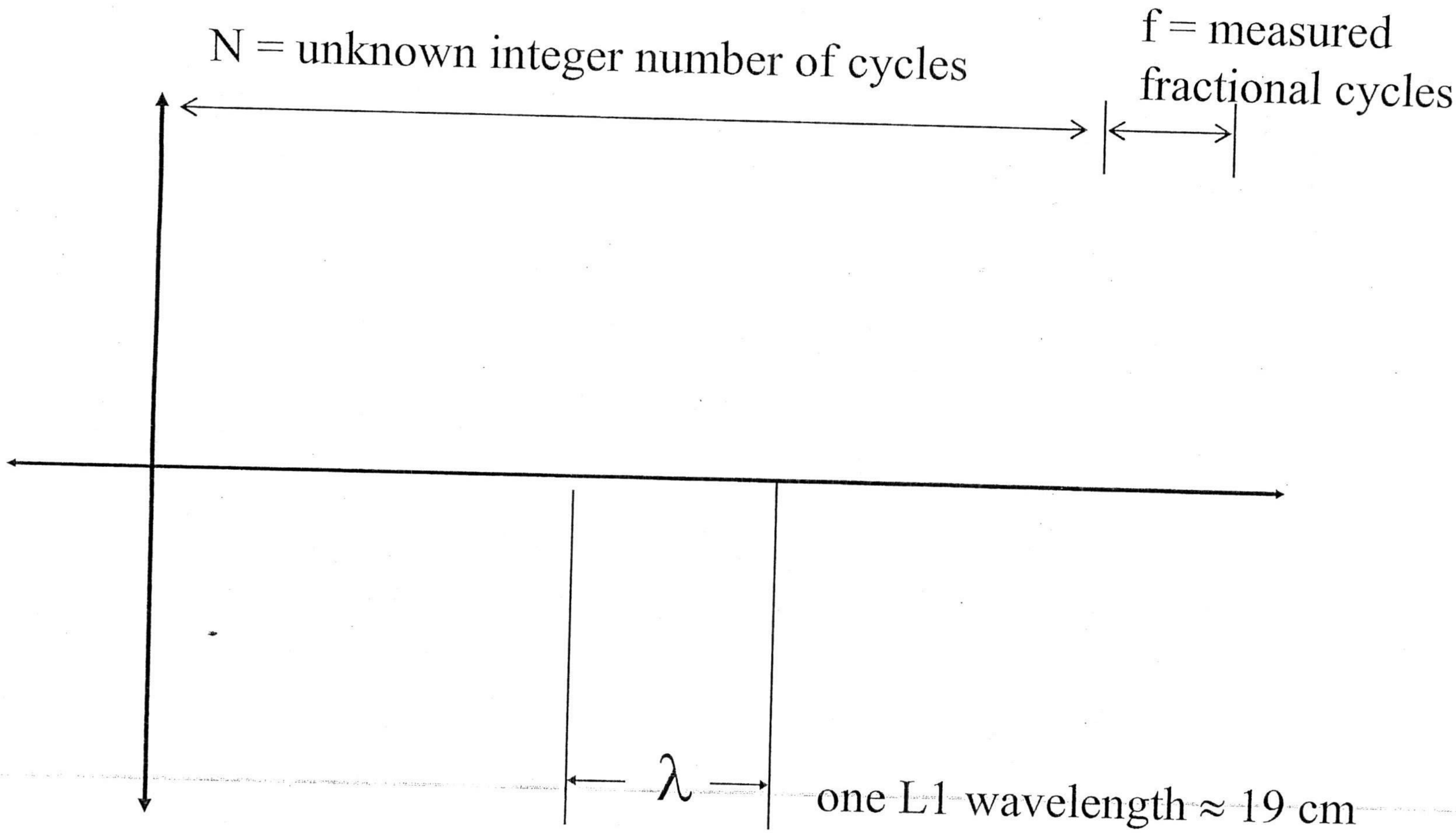


Finding Δt for each GPS signal tracked is called "code correlation"

- Δt is proportional to the GPS-to-receiver range
- Four pseudorange measurements can be used to solve for receiver position

Carrier Phase

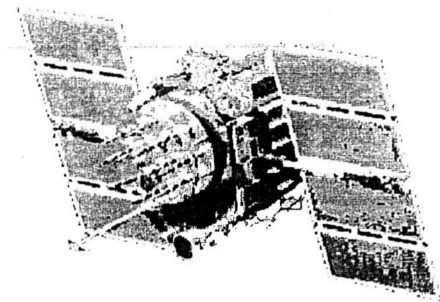
The Doppler-shifted GPS carrier signal is mixed with the receiver reference signal to produce a beat wave whose phase can be measured with mm-level precision



The Global Positioning System (GPS)

- Space-based radio-navigation system provides highly accurate position, velocity, and time information
  - Simple/inexpensive user equipment
  - Global, all-weather, secure, etc.
- Tremendous growth in the civilian user base
  - Civil Agencies: NASA, NOAA, FAA, DoT, etc.
  - Commercial: Telecom, Surveying, Agriculture, Mining, etc.
  - Recreation: Boating, Hiking, Golfing, etc.
  - GPS has become a critical component of the U.S. (and global) information infrastructure
- Satellite navigation market is valued in the billions of dollars today, and is growing rapidly
  - Civil uses account for vast majority

GPS History



Developed by the US Department of Defense

- Early GPS program driver was Trident Missile Program (Submarine launched ICBM)
- Satellites carry a nuclear detonation detection payload

Early Satellite Navigation Systems

- TRANSIT
- Timation (first atomic frequency standards flown in space)
- USAF 621B Program (use of PRN codes for ranging)

First prototype GPS satellite launched in 1978

First Block II (Operational) GPS satellite launched 1989

Full Operational Capability declared in 1994

GPS Provides Two Levels of Service...

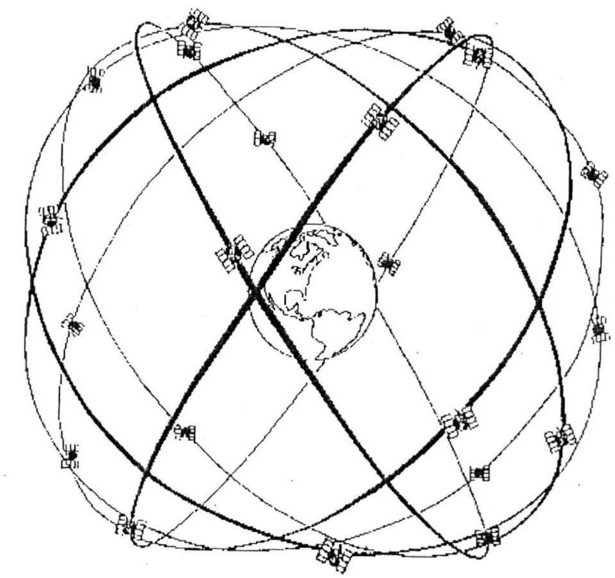
- **Standard Positioning Service (SPS)**
  - C/A code on L1 available to anyone
  - Selective Availability (SA): Deliberate degradation of the full SPS accuracy (Deactivated May 2, 2000)
- **Precise Positioning Service (PPS)**
  - P(Y) code on L1 and L2, encrypted to restrict access to authorized (military) users
    - Longer code less susceptible to jamming/interference
    - Encryption provides protection for authorized users against a hostile force transmitting deliberately incorrect GPS signals (spoofing)
- **Authorized users can directly correct for atmosphere delay errors by dual frequency tracking**

Current GPS Signal Structure

Two L-band carrier frequencies

L_1 = 1575.42 MHz L_2 = 1227.60 MHz

Two PRN Codes – Uniquely Identify Each Satellite

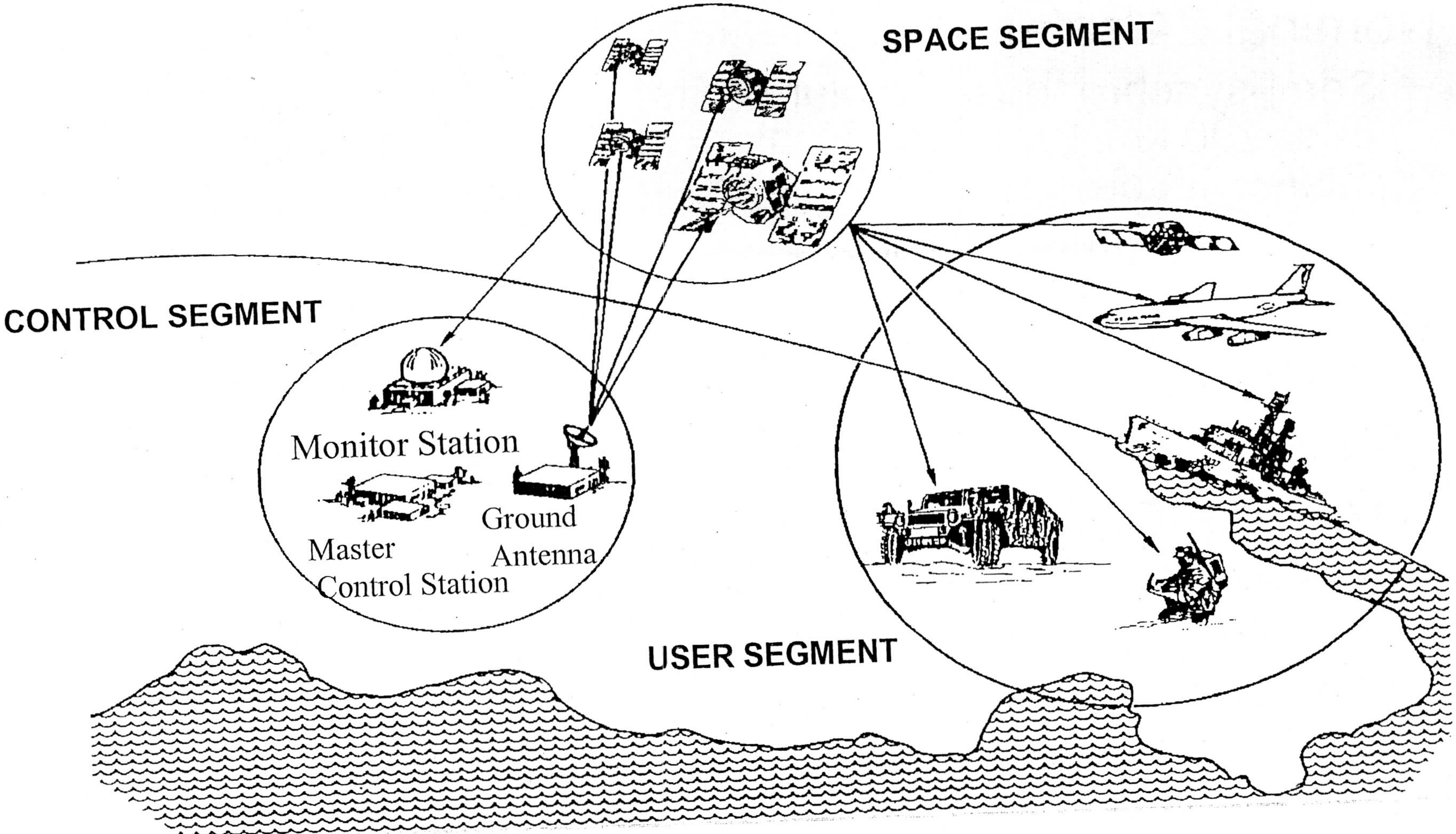


- C/A: Coarse Acquisition (Civilian) Code
  - 1 millisecond repeat interval
  - Available to all users, but only on L1
- P(Y): Military Code
  - 267 day repeat interval
  - Available on L1 and L2
  - Y code is encrypted version of P code – code sequence not published

Code modulated with Navigation Message Data

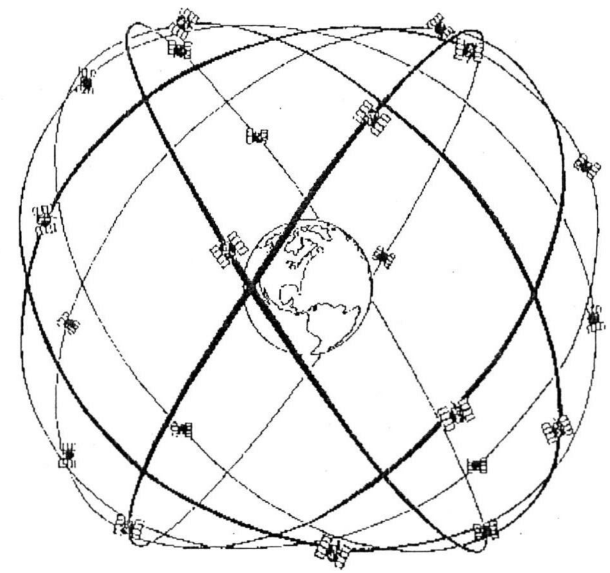
- Provides ephemeris data and clock corrections for the GPS satellites
- Low data rate (50 bps)

GPS System Configuration - Three Major Segments



Space Segment

- Nominal 24 satellite constellation
  - Semi-synchronous, circular orbits (~20,200 km/10,900 nautical miles altitude)
  - Repeating ground tracks (11 hours 58 minutes)
  - Six orbital planes, inclined at 55 degrees, four vehicles per plane
  - *designed for global coverage (at least 4 sats in view)*



- Redundant cesium and/or rubidium clocks on board each satellite
- In recent years there have been two to three replenishment launches per year

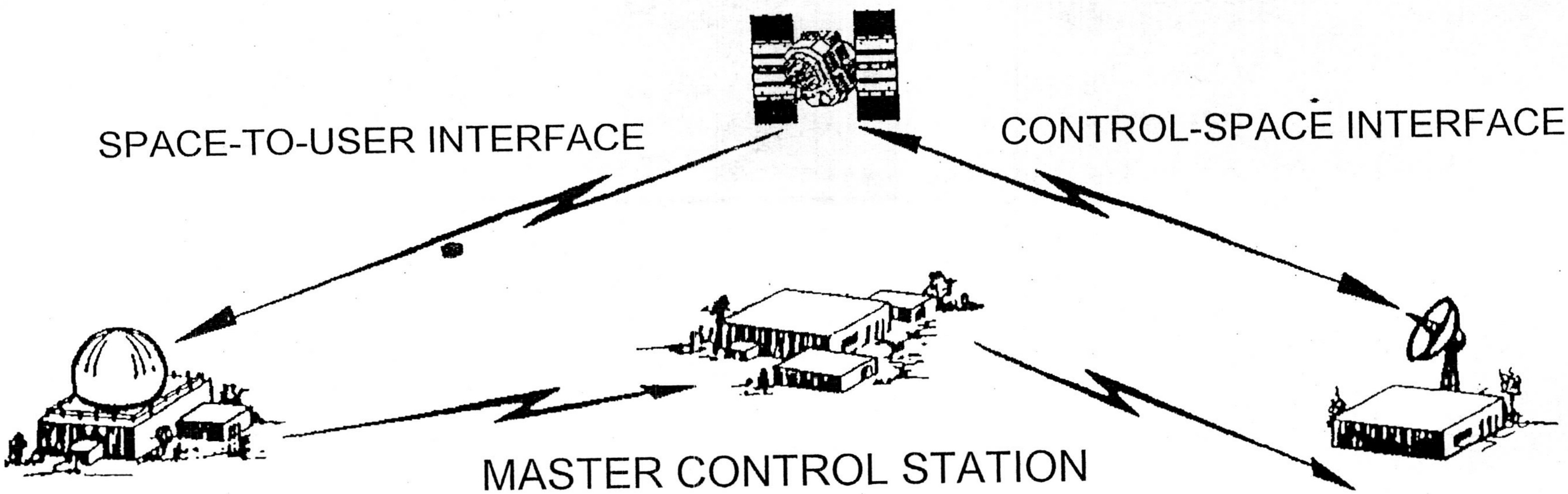
Control Segment

SPACE VEHICLE

Broadcasts the SIS PRN codes, L-band carriers, and 50 Hz navigation message stored in memory

SPACE-TO-USER INTERFACE

CONTROL-SPACE INTERFACE



MASTER CONTROL STATION

- Checks for anomalies
- Computes SIS portion of UERE
- Generates new orbit and clock predictions
- Builds new upload and sends to GA

MONITOR STATION

- Sends raw observations to MCS

GROUND ANTENNA

- Sends new upload to SV

Control Segment – Monitor Stations

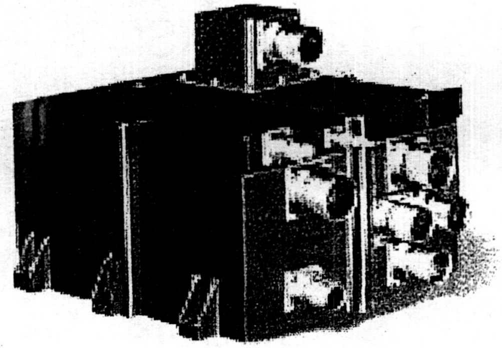
Existing GPS Monitor Stations

- Hawaii, Ascension Island, Diego Garcia, Kwajalein, and Colorado Springs

GPS User Segment

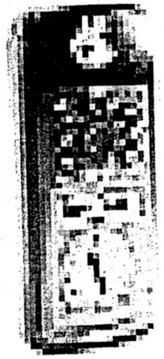
- GPS receivers are specialized "radios" that track GPS signals and produce position and velocity solutions
  - Wide range of cost/sophistication depending on the application
- Signals from 4 or more GPS satellites are required, but 8-10 are typically available at any time
- Civil (SPS) receivers typically track only the L1 C/A signal
- PPS receivers have special keys that allow tracking of the military P(Y) code over both L1 and L2
  - Dual Frequency "Codeless" receivers allow non-authorized users to track the the signals on L2 without knowledge of the code

Military Spacecraft
(~$1,000,000)



courtesy General Dynamics

Consumer Recreation
(~$100)

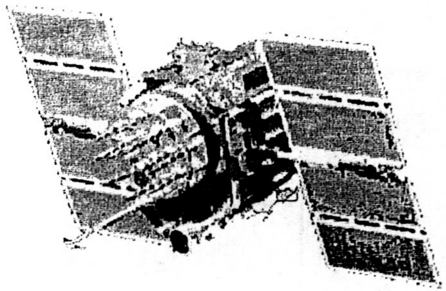


courtesy Garmin

GPS Augmentations

- WAAS
  - WAAS provides augmentation information to GPS receivers to enhance the accuracy and reliability of position estimates
  - Space Based Augmentation System (SBAS) covering nearly all of the National Airspace System (NAS)
  - Commissioned July 2003
- LAAS
  - Augmentation to GPS that focuses its service on the airport area (approximately a 20-30 mile radius)
  - Broadcasts correction message via a very high frequency (VHF) radio data link from a ground-based transmitter
- NASA Global Differential GPS (DGPS)
  - NASA provides real-time corrections to the broadcast GPS satellite ephemeris and clock data
  - Reduces ephemeris and clock errors from a few meters to a few cm

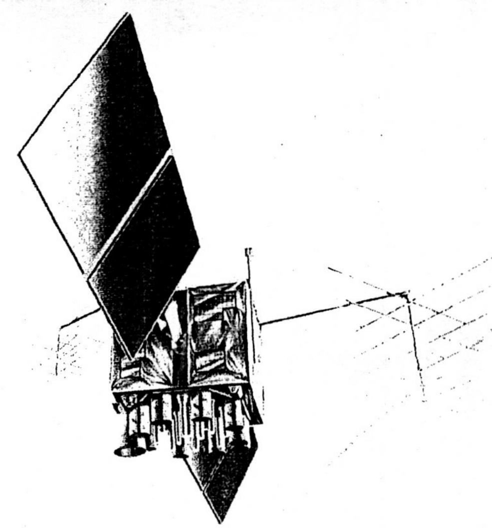
Current GPS Constellation Status



Block II/IIA
Built by Boeing Aerospace
Launched 1989 - 1997

- Currently 29 satellites on-orbit
  - 1 Block II
  - 16 Block IIA
  - 12 Block IIR
- There have been three launches since Dec 2003

- Age Summary
  - All satellites have greatly exceeded original design lifetime
  - 13 satellites are more than 10 years old
  - Several are "single string"



Block IIR/IIR-M
Built by Lockheed Martin
Launched 1997 - 2007

SPS Performance

source: GPS SPS Performance Standard, Department of Defense, Oct 2001

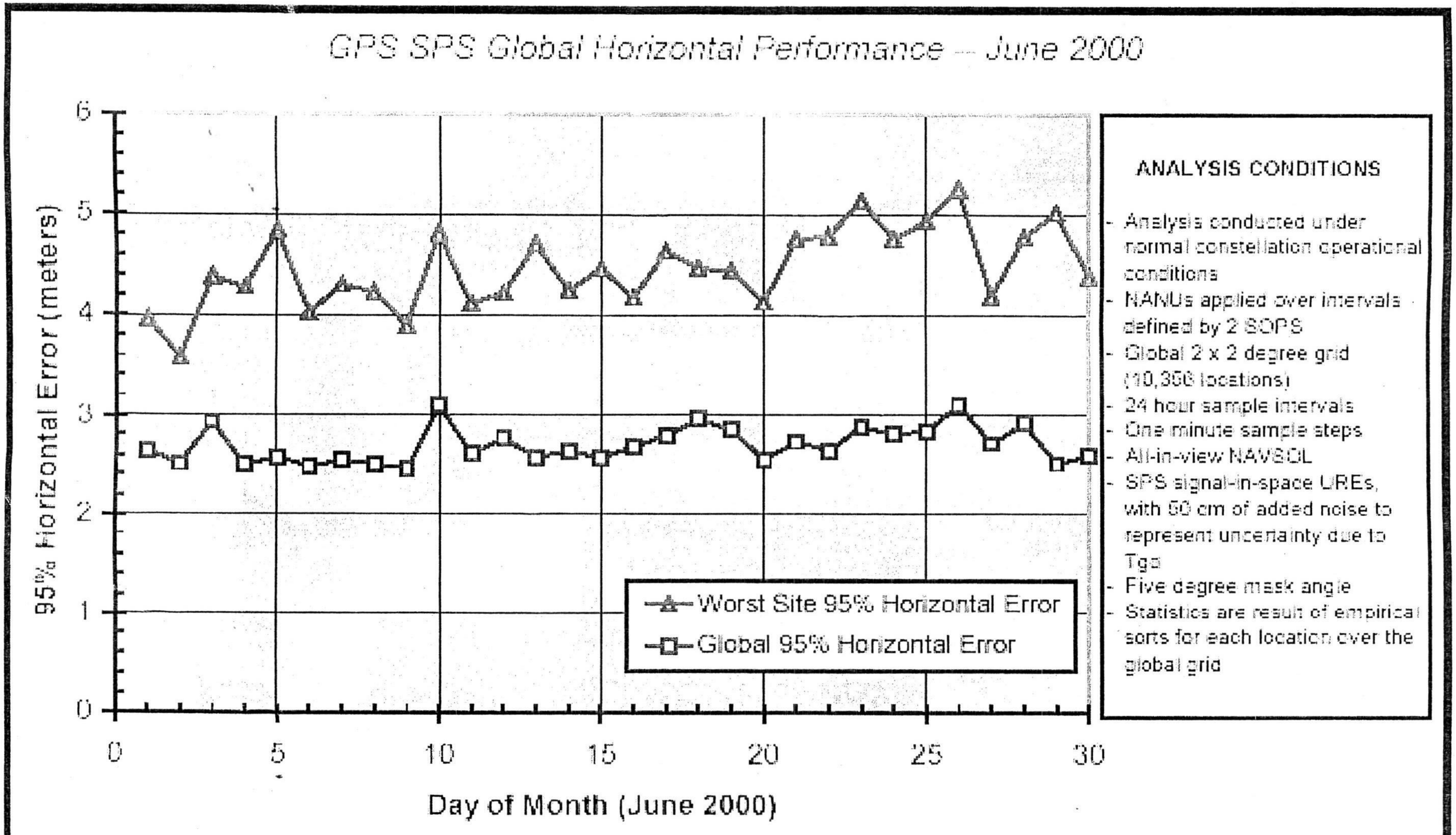


Figure A-5-7. Typical Example of GPS SPS SIS Horizontal Performance – June 2000

SPS Performance

source: GPS SPS Performance Standard, Department of Defense, Oct 2001

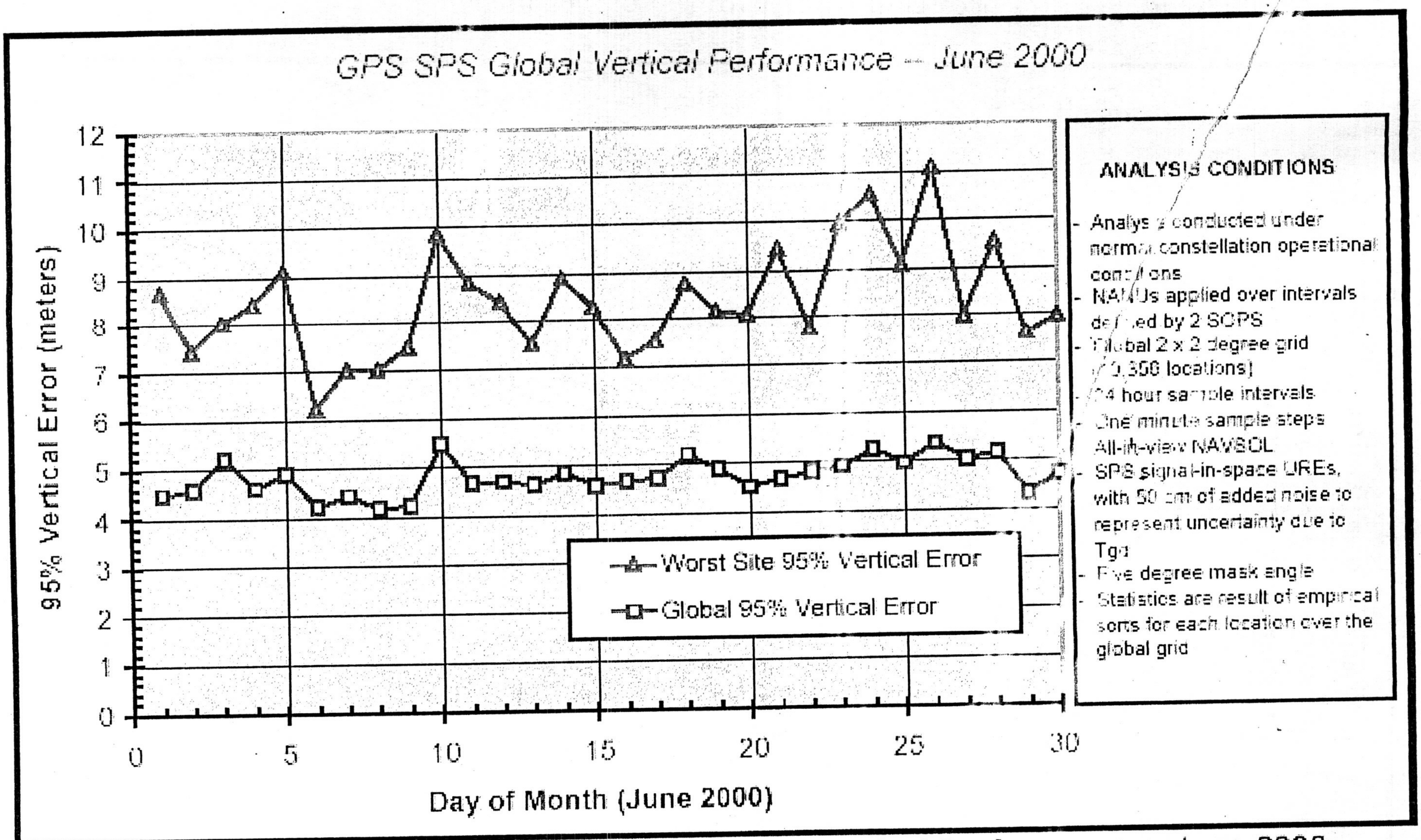


Figure A-5-8. Typical Example of GPS SPS SIS Vertical Performance – June 2000

SPS Performance

source: GPS SPS Performance Standard, Department of Defense, Oct 2001

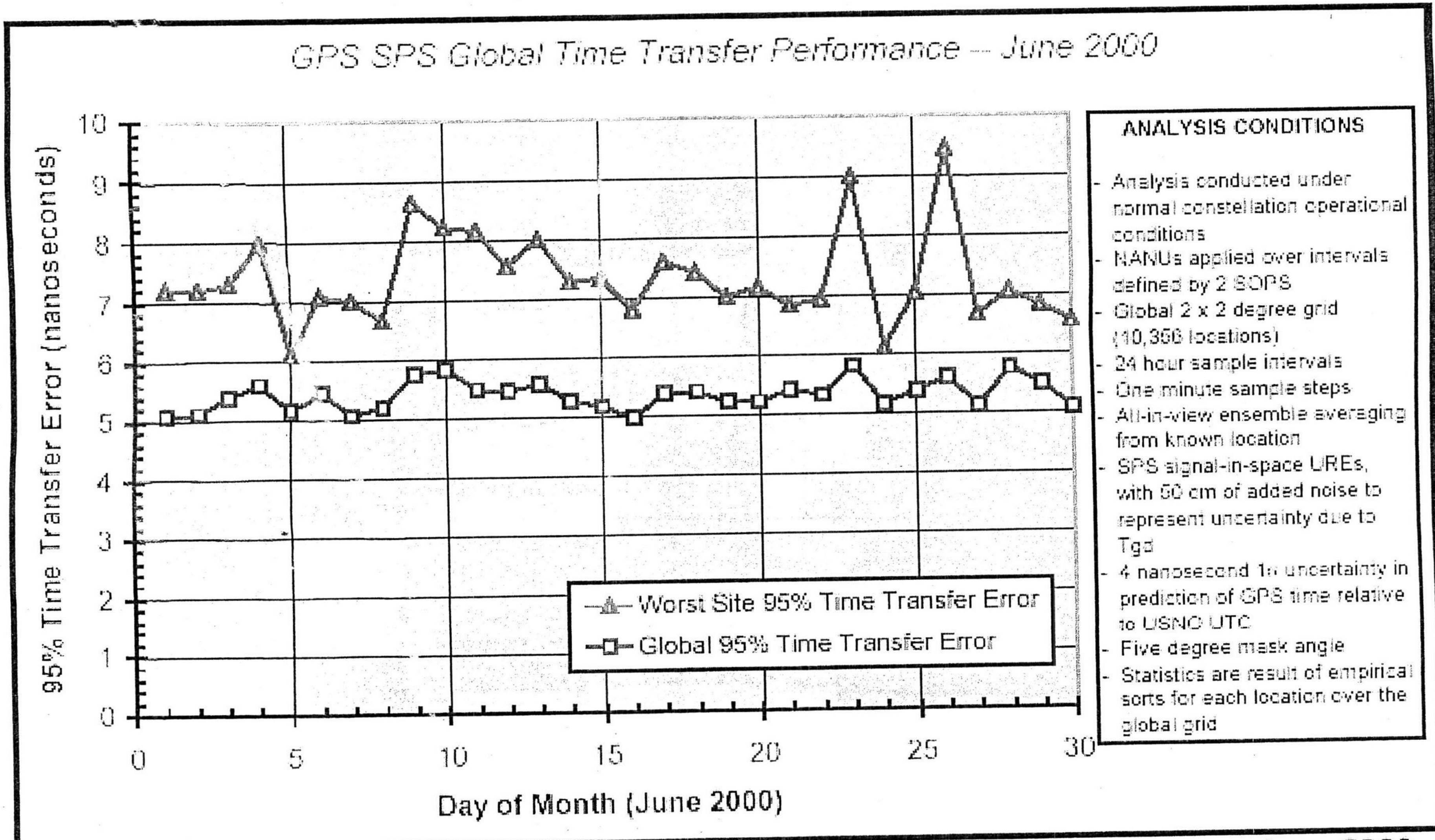
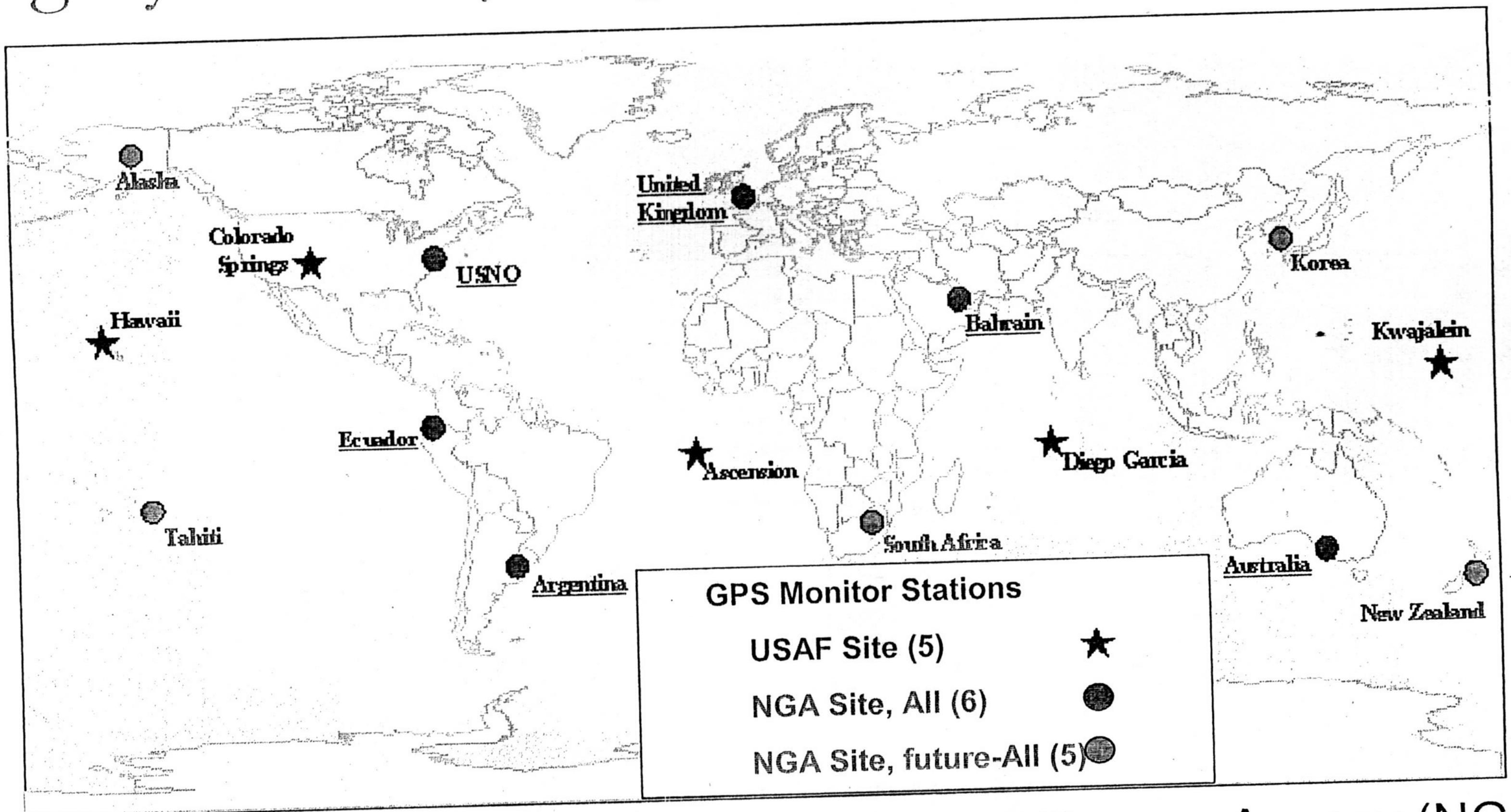


Figure A-5-10. Typical Example of GPS SPS SIS Time Transfer Performance – June 2000

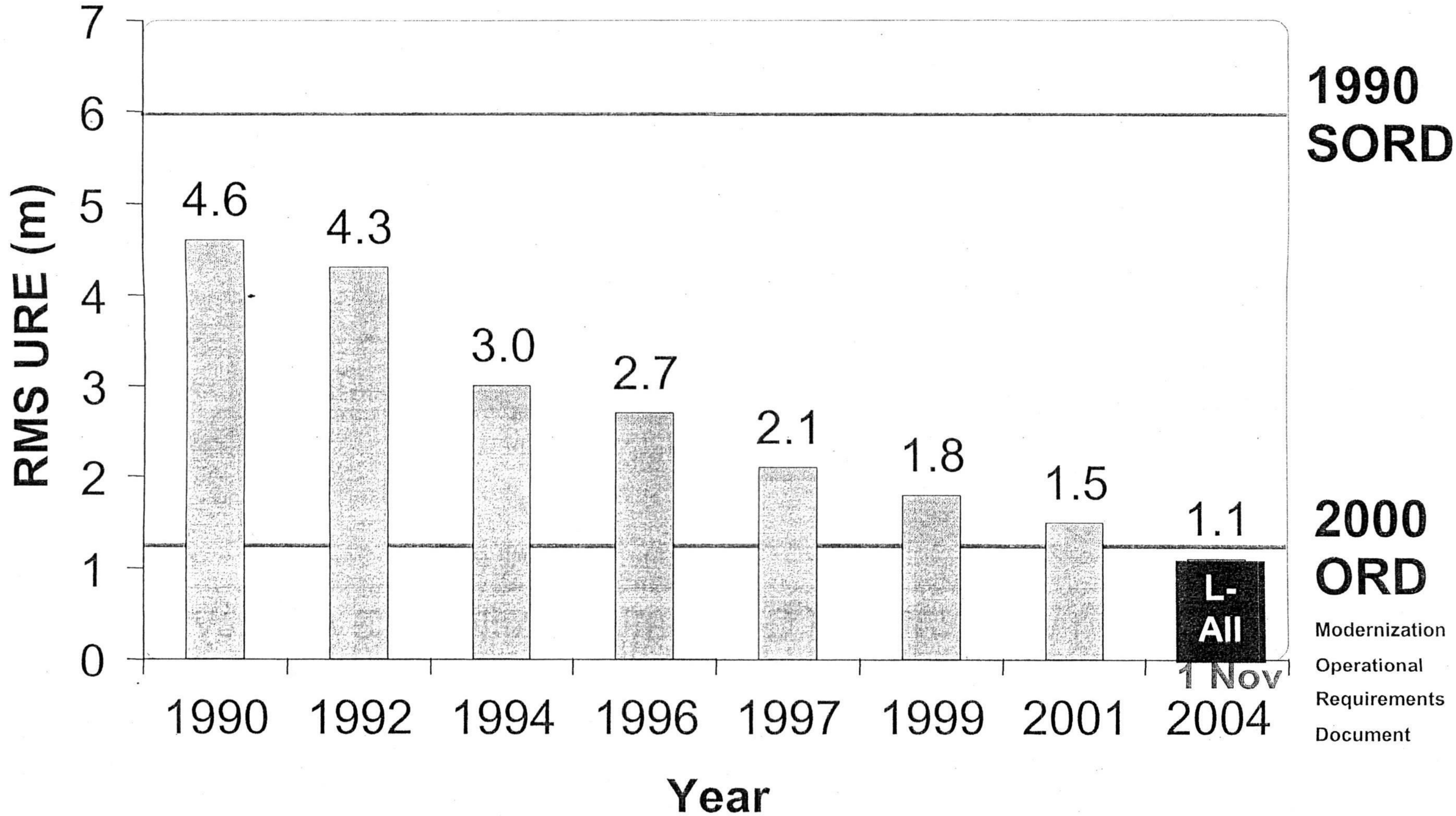
Legacy Accuracy Improvement Initiative (L-AII)



- USAF working with National Geospatial-Intelligence Agency (NGA) to incorporate NGA ground stations into GPS network
  - Reduce range error and improve accuracy
  - Initially six NGA sites will be added
  - By 2006, 5 more NGA sites will be added to L-AII

Presented by Col Mark Crews at the 44th Meeting of the CGSIC, Long Beach, CA, September 2004.

URE Performance History



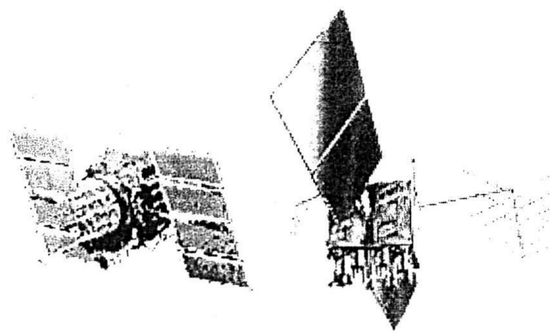
Presented by Col Mark Crews at the 44th Meeting of the CGSIC, Long Beach, CA, September 2004.

GPS Modernization

- Civil Users Currently Limited to One GPS Signal
  - C/A-code at L1 frequency (1575.42 MHz)
    - Low power signal, susceptible to interference, not intended for precision navigation
- Adds a New Civil Signal at L2
  - L2C code at L2 frequency (1227.60 MHz)
    - Better signal properties (similar to P code)
    - Allows dual frequency GPS reception by civil users
  - First signal in space expected 2005 (Block IIR-M)
- Adds a Third Civil Signal (L5)
  - P-type codes at L5 frequency (1176.45 MHz)
    - Higher power signal, intended for precision navigation
  - First signal in space expected ~2006-07 (Block IIF)

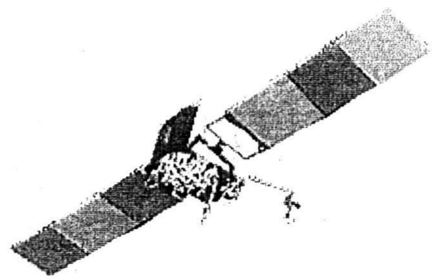
GPS Modernization

Block IIA/IIR



<u>IIA / IIR</u>: Basic GPS
- C/A civil signal (L1C/A)
- Std Service, 16-24m SEP
- Precise Service, 16m SEP
  - L1 & L2 P(Y) nav

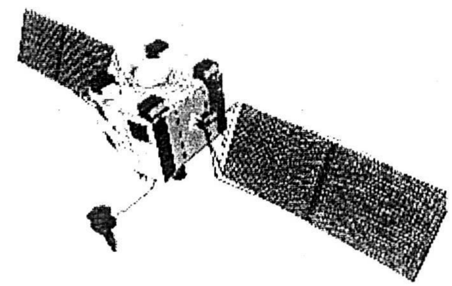
Block IIR-M, IIF



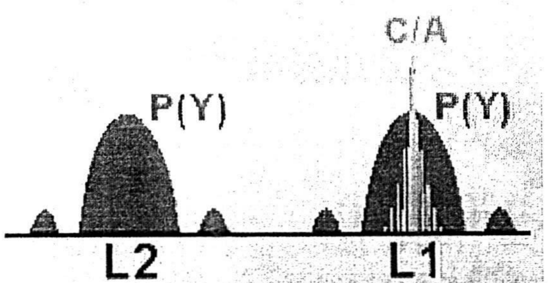
<u>IIR-M</u>: IIA/IIR capabilities &
- 2nd civil signal (L2C)
- New military code
- Flex A/J power (+7dB)

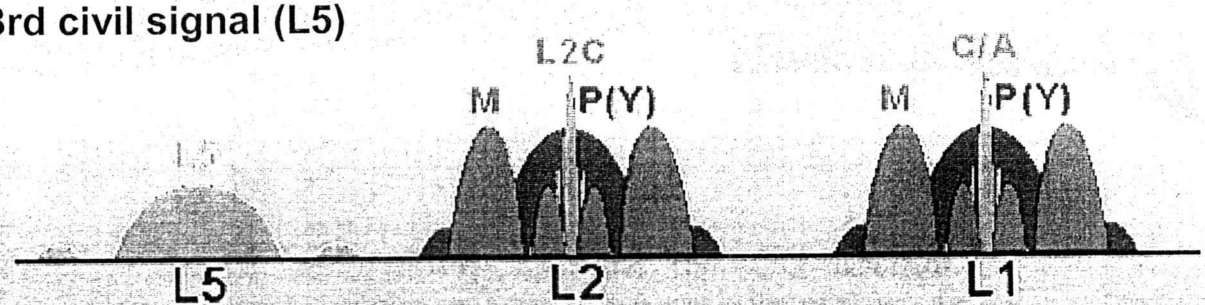
<u>IIF</u>: IIR-M capability plus
- 3rd civil signal (L5)

Block III



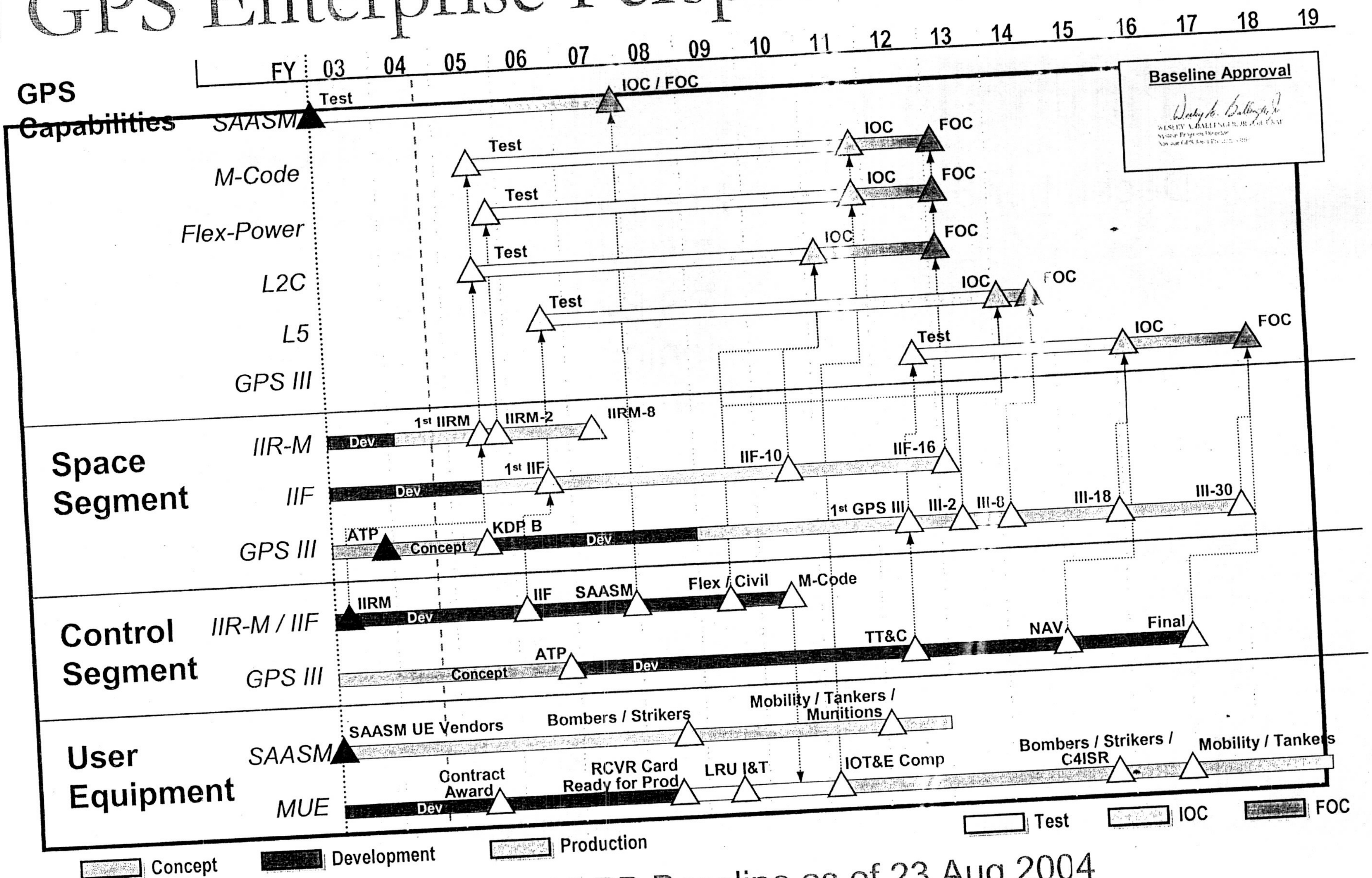
<u>III</u>: IIF capabilities &
- Improved civil signal (L1C)
- Increased accuracy (4.8-1.2m)
- DASS (Distress Alerting Sat Sys)
- Navigation surety
  - Increased A/J power (+20 dB)





Presented by Col Mark Crews at the 44th Meeting of the CGSIC, Long Beach, CA, September 2004.

GPS Enterprise Perspective Schedule



JPO Approved Baseline Based on FY05 PB
Updated as of: 23 Aug 04 SMR

FY05 PB Baseline as of 23 Aug 2004

Presented by Col Mark Crews at the 44th Meeting of the CGSIC, Long Beach, CA, September 2004

U.S. Space-Based Positioning, Navigation, and Timing Policy

- On December 8, 2004, the President signed the new U.S. Space-Based Positioning, Navigation, and Timing Policy.
- Replaces the Interagency GPS Executive Board with a National Space-Based Positioning, Navigation, and Timing Executive Committee, co-chaired by the Deputy Secretaries of Defense and Transportation, or their designated representatives.
- Reaffirms the U.S. Government's commitment to provide on a continuous, worldwide basis civil space-based, positioning, navigation, and timing services free of direct user fees, and to continue to improve these services in the future.
- Fact sheet released by the Office of Science and Technology Policy:

http://www.ostp.gov/html/FactSheetSPACE-BASEDPOSITIONINGNAVIGATIONTIMING.pdf

GPS References

- B.W. Parkinson et al. (editors), *Global Positioning System: Theory and Applications*, Vol. 1&2, Progress in Astronautics and Aeronautics, 1997.
- E. Kaplan (editor), *Understanding GPS: Principles and Applications*, Artech House Publishers, 1996.
- P. Misra, P. Enge, *Global Positioning System: Signals, Measurements, and Performance*, Ganga-Jamuna Press, 2001.
- http://gps.faa.gov/index.htm
- http://www.igeb.gov/

GPS References:

Civil GPS Information Center (GPSIC)

From the DOT and the Coast Guard

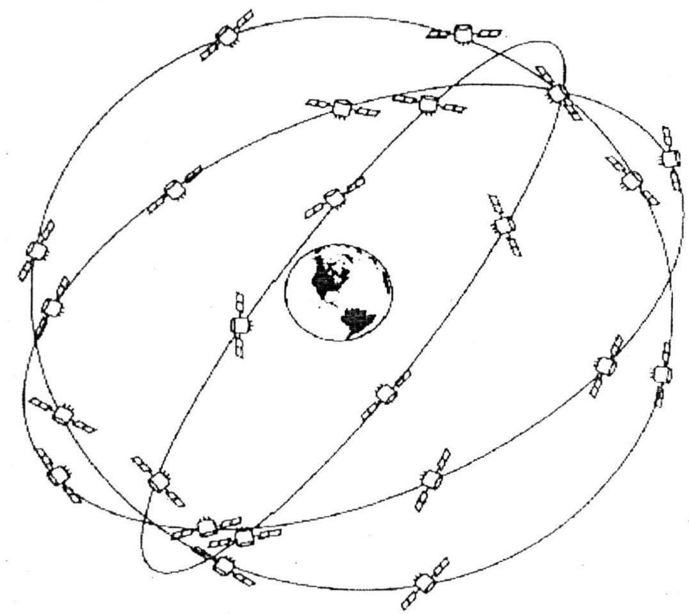
All Services Free

- Information Available:
  - Constellation Status
  - Future Status
  - Almanac
  - General GPS Resources
- Information Media:
  - Computer Bulletin Boards (703) 313-5910
  - Voice Tape (703) 313-5907
  - Resource Person (703) 313-5900
  - Web Page http://www.navcen.uscg.gov/GPS/default.htm
  - Civil GPS Service Interface Committee (CGSIC)

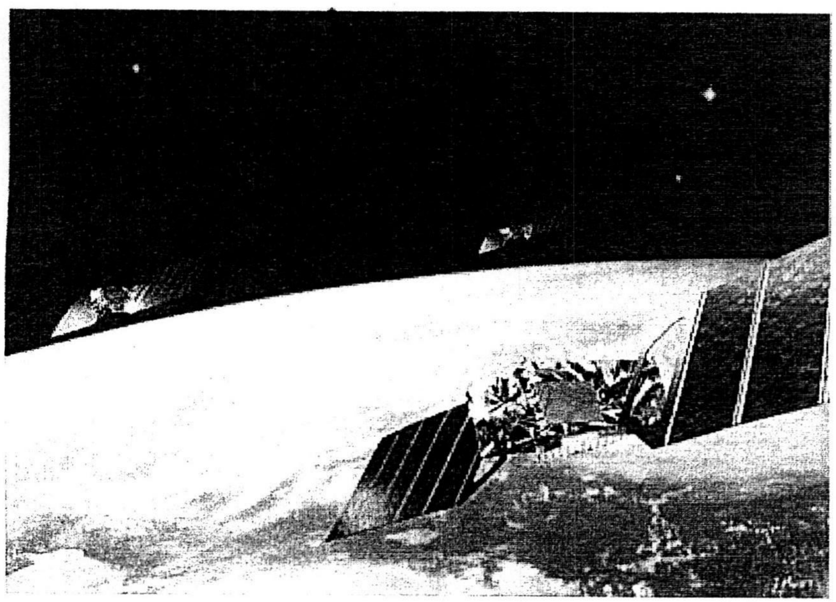
GPS References:
Federal Radionavigation Plan

- Document revised into two separate documents
  - Federal Radionavigation Plan
    - Policy and plans portions of current document
    - Dynamic, may be updated annually
  - Federal Radionavigation Systems
    - System descriptions
    - Basically static, update as required
- Current: http://www.navcen.uscg.gov/pubs/frp2001

Other Satellite Navigation Systems

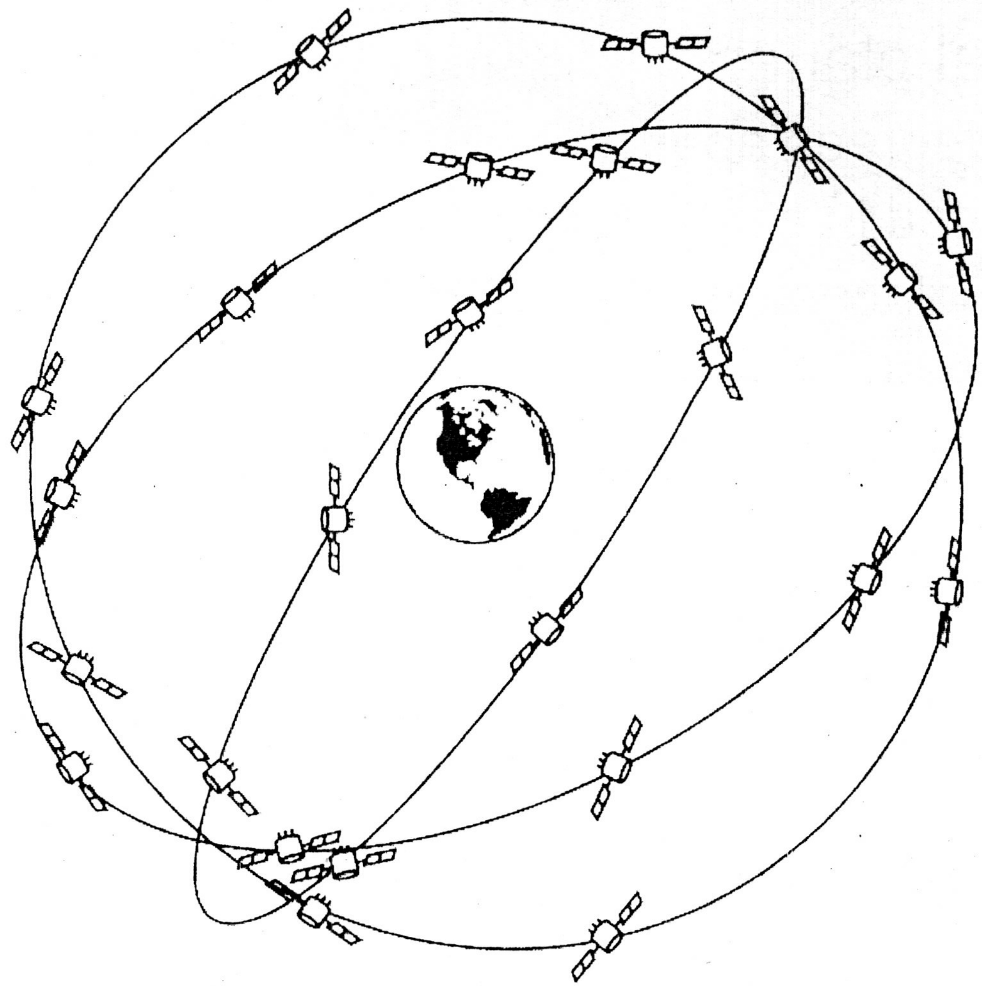


- **GLONASS** (Russia)
- **Galileo** (European Union)
- **QZSS** (Japan)



- China, India, Australia among other nations considering new GNSS systems or augmentations

GLONASS: GLObal NAvigation Satellite System



GLONASS Satellite Constellation

- Operated by the Coordinational Scientific Information Center of the Russian Federation Ministry of Defense
- First satellite launched in 1982, constellation not fully populated today
- Russian Government has recently made a renewed commitment to replenish and modernize the GLONASS constellation

GLONASS Constellation

- 24 satellites in 3 orbital planes
  - ascending nodes 120 degrees apart
  - 8 satellites equally spaced in each plane
  - argument of latitude displacement of 45 degrees
  - planes have 15 degrees argument of latitude displacement
- Circular 19,100 km orbit
  - inclination angle of 64.8 degrees
- Complete one orbit in 11 h 15 min 44 s, minimum of 5 satellites are in view to users continuously, world-wide .
- Cesium clocks on board satellites

GLONASS Signal Characteristics

- Each satellite transmits signal on unique frequency (FDMA)
  - Some satellites may use the same frequencies, but those satellites are placed in antipodal slots of orbit planes and they do not appear at the same time in a user's view
- Two frequency bands
  - L1 = 1602 + n*0.5625 MHz
  - L2 = 1246 + n*0.4375 MHz
  - Where n is frequency channel number (n=0,1,2,...)
- Standard Precision (SP) Signal
  - PRN code clock rate 0.511 MHz
  - repeats each millisecond
  - civilian use
- High Precision (HP) Signal
  - PRN code clock rate 5.11 MHz
  - repeats each second,
  - modulated by special code, includes anti-spoofing capability
  - military use

GLONASS Control System

Several Command Tracking Stations (CTS) throughout Russia

- St. Petersburg, Ternopol, Yeniseisk, Komsomolsk, Balkhash
- track satellites in view and accumulate ranging data and telemetry from the satellite signals
- transmit updated information to satellites, as well as other control information
- ranging data is periodically calibrated using laser ranging devices at Quantum Optical Tracking Stations within GCS. Each satellite specially carries laser reflectors for this purpose.

System Control Center (SCC) in Krasnoznamensk (Moscow region)

- process CTS site information to determine satellite clock and orbit states and update the navigation message for each satellite.

GLONASS Control System (cont)

- **GLONASS system time-scale**
  - based on high-precision hydrogen clocks
  - relay signals to the phase control system (PCS) which monitors satellite clock time/phase as transmitted by the navigation signals and determines satellite corrections for upload
  - synchronized with UTC(SU)
  - also synchronized with UTC(CIS), which is maintained by the All Union Institute for Physical, Technical, and Radio-Technical Measurements (VNIIFTRI) in Mendeleevo, near Moscow
  - uses leap seconds
- **Ephemeris data in the Earth Parameter System 1990 (PZ-90), unlike GPS WGS-84**

United States – Russian Federation Joint Statement

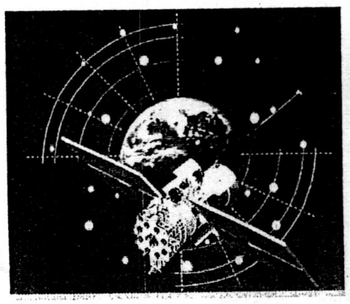
Delegations of the United States and the Russian Federation met in Washington D.C. on December 9-10, 2004, to continue discussions on matters relating to GPS and GLONASS cooperation.

Both sides reiterated their commitment to continuing these talks and reaffirmed that the United States and the Russian Federation intend to continue to provide the GPS and GLONASS civil signals appropriate for commercial, scientific and safety of life use on a continuous, worldwide basis, free of direct user fees.

Full text at:
http://www.state.gov/r/pa/prs/ps/2004/39748.htm

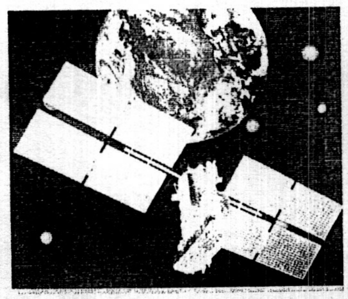
GLONASS Modernization*

GLONASS
1982-2007



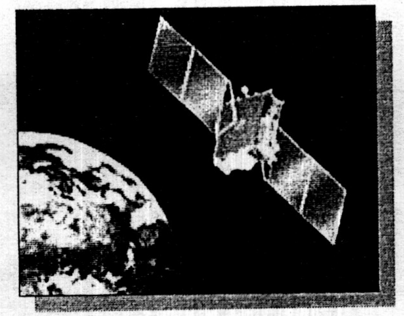
Developer NPO PM
Producer PO "Polyot"
Total launched 79 SV
Ordered 3 SV
In orbit 10 SV
Life-time 3 years

GLONASS-M
2003-2015



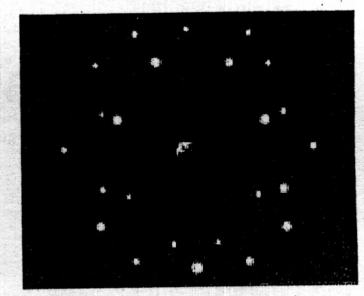
Developer NPO PM
Producer NPO PM
Ordered 9 SV
In orbit 1 SV
To be ordered 6
Life-time 7 years
2nd civil signal

GLONASS-K
2008-2025



Developer NPO PM
D&D phase
To be ordered up to 27 SV
Life-time 10 years
3rd civil signal

GLONASS-KM
2015-.....



Requirement definition
since 2002 г.

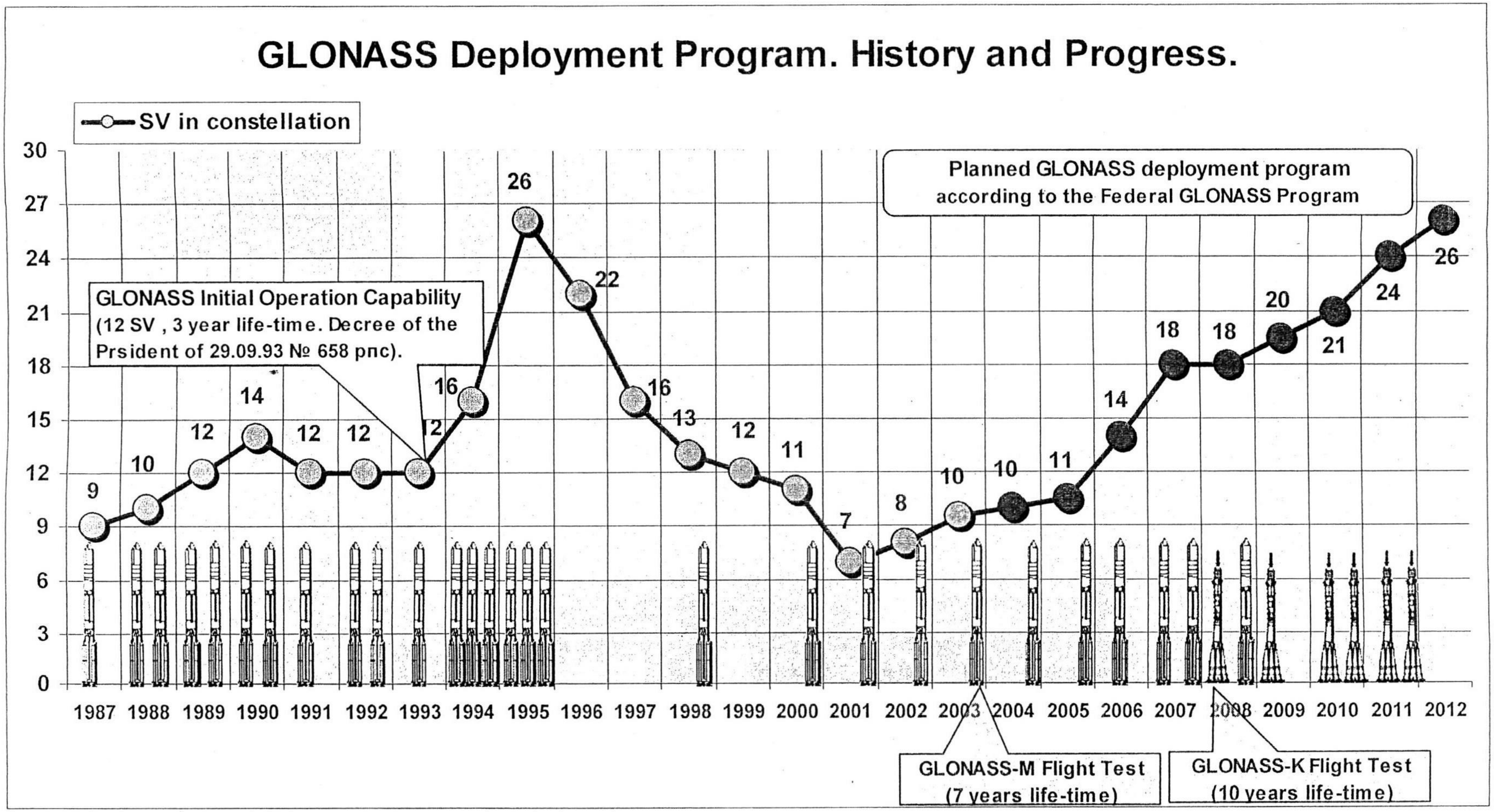
Ground control segment modernization
Navigation (OD$TS) system modernization
GLONASS augmentation system implementation
System certification for safety of life applications

Navigation service market development

Search and Rescue service implementation
Supplementary functions (TBD)

*From "Developments of the GLONASS system and GLONASS Service," presented in Washington, DC, December, 2004.

GLONASS Launch Program*

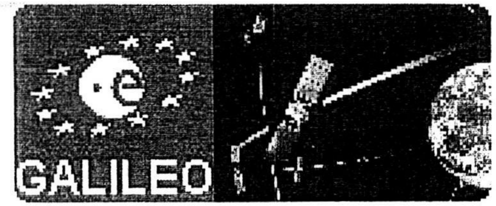


*From "Developments of the GLONASS system and GLONASS Service," presented in Washington, DC, December, 2004.

GLONASS References

- http://www.glonass-center.ru

GALILEO



- Proposed European Global Navigation Satellite System
- Galileo is a joint initiative of the European Commission (EC) and the European Space Agency (ESA).
- Consists of 30 medium Earth orbit satellites, associated ground infrastructure, and regional/local augmentations.
- Will offer a basic service for free (Open Service), but will charge user fees for premium services.
- Development cost approximately €3.2 billion
- First signal in space 2005, operational in 2008

The GALILEO Satellite Services

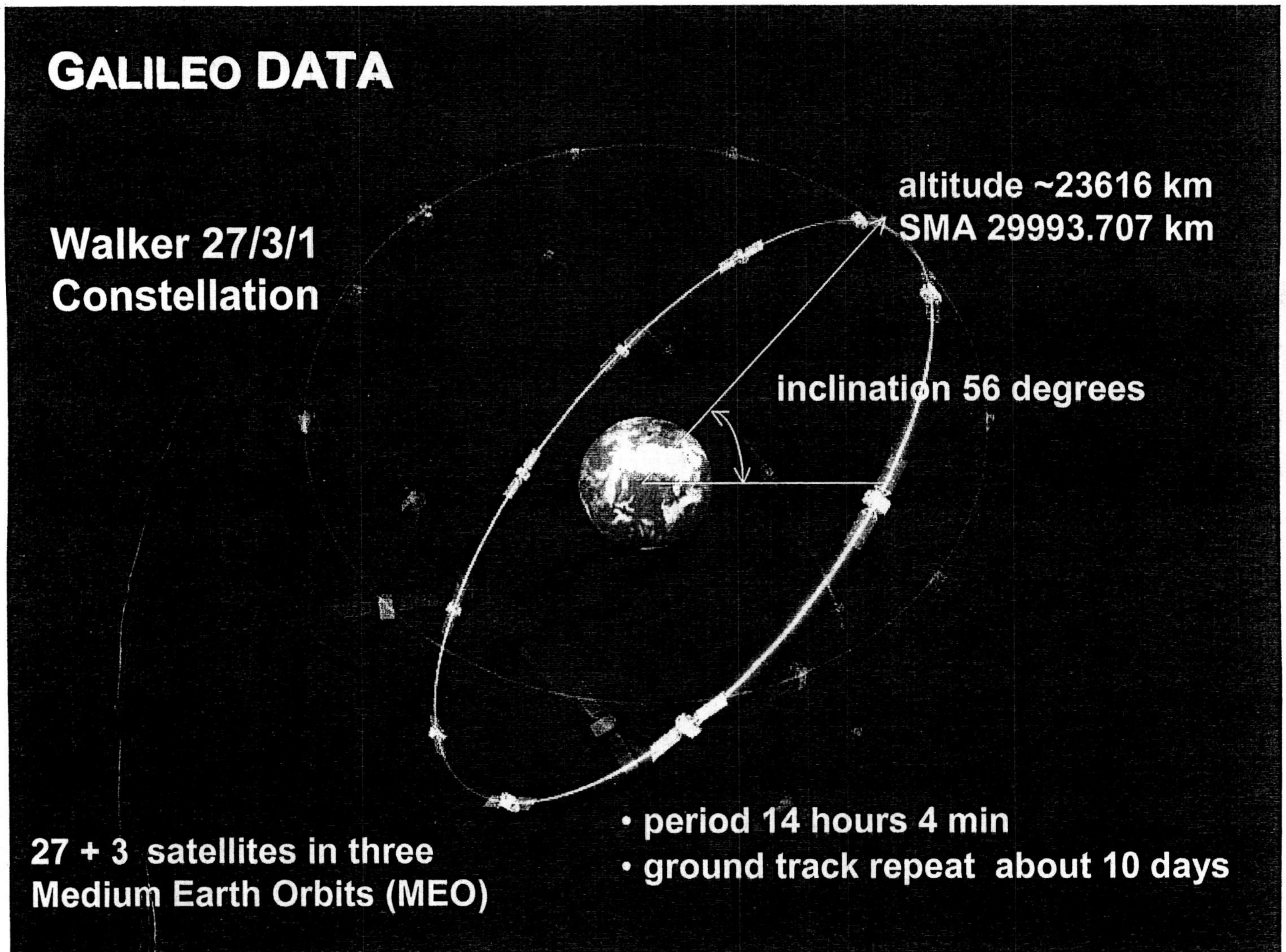
Position, Velocity and Time Services:

- **Open Service** - providing positioning, navigation and timing services, free of charge, for mass market navigation applications (future GPS SPS)
- **Commercial Service** - provides added value over the Open Service providing commercial revenue, such as dissemination of encrypted navigation related data (1 KBPS), ranging and timing for professional use - with service guarantees
- **Safety of Life Service** - Comparable with “Approach with Vertical Guidance” (APV-II) as defined in the ICAO Standards and Recommended practices (SARPs), and includes Integrity
- **Public Regulated Service** - for applications devoted to European/National security, regulated or critical applications and activities of strategic importance - Robust signal, under Member States control

Support to Search and Rescue

- Search and Rescue Service coordinated with COSPAS SARSAT

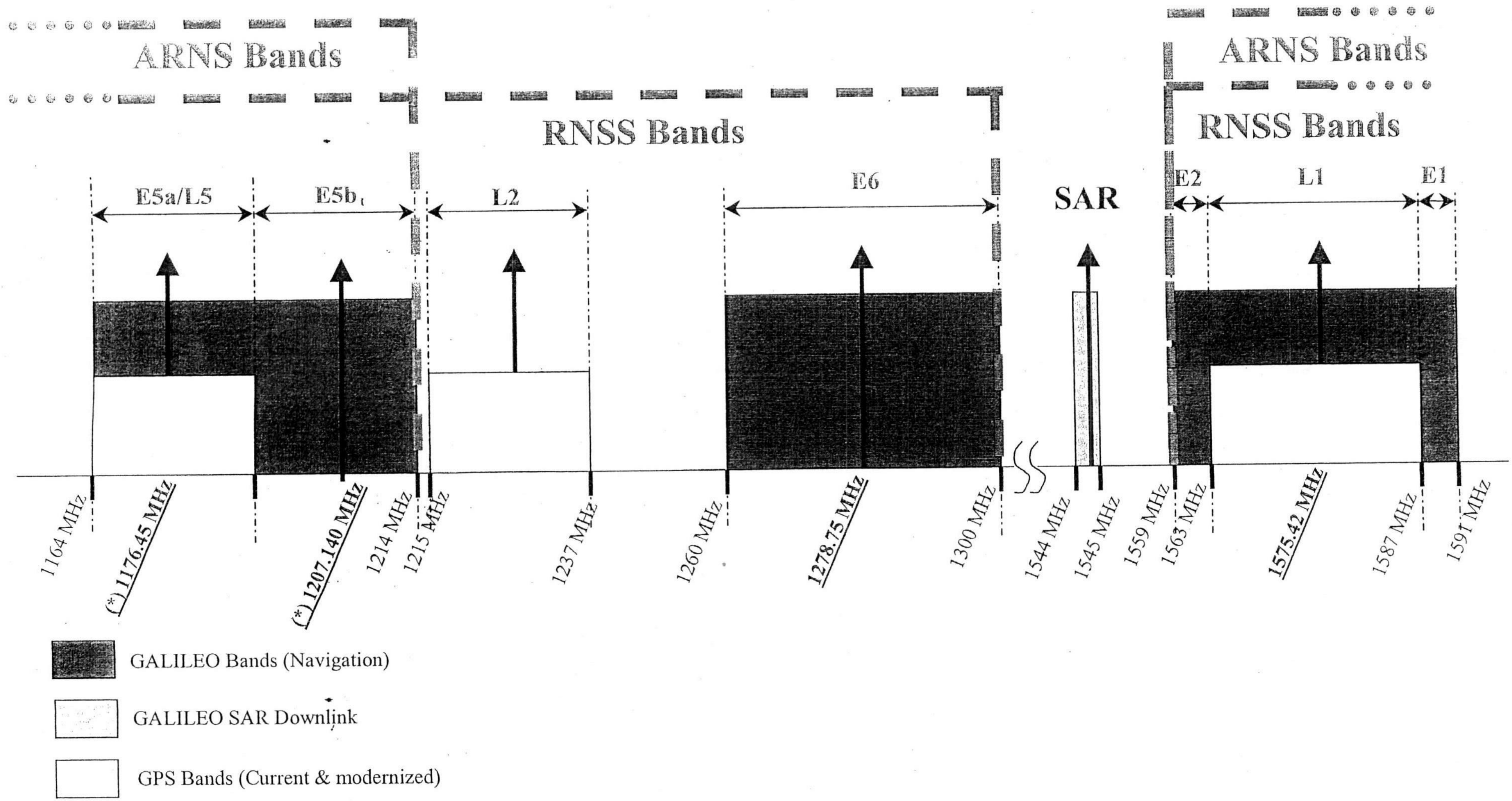
Constellation Configuration

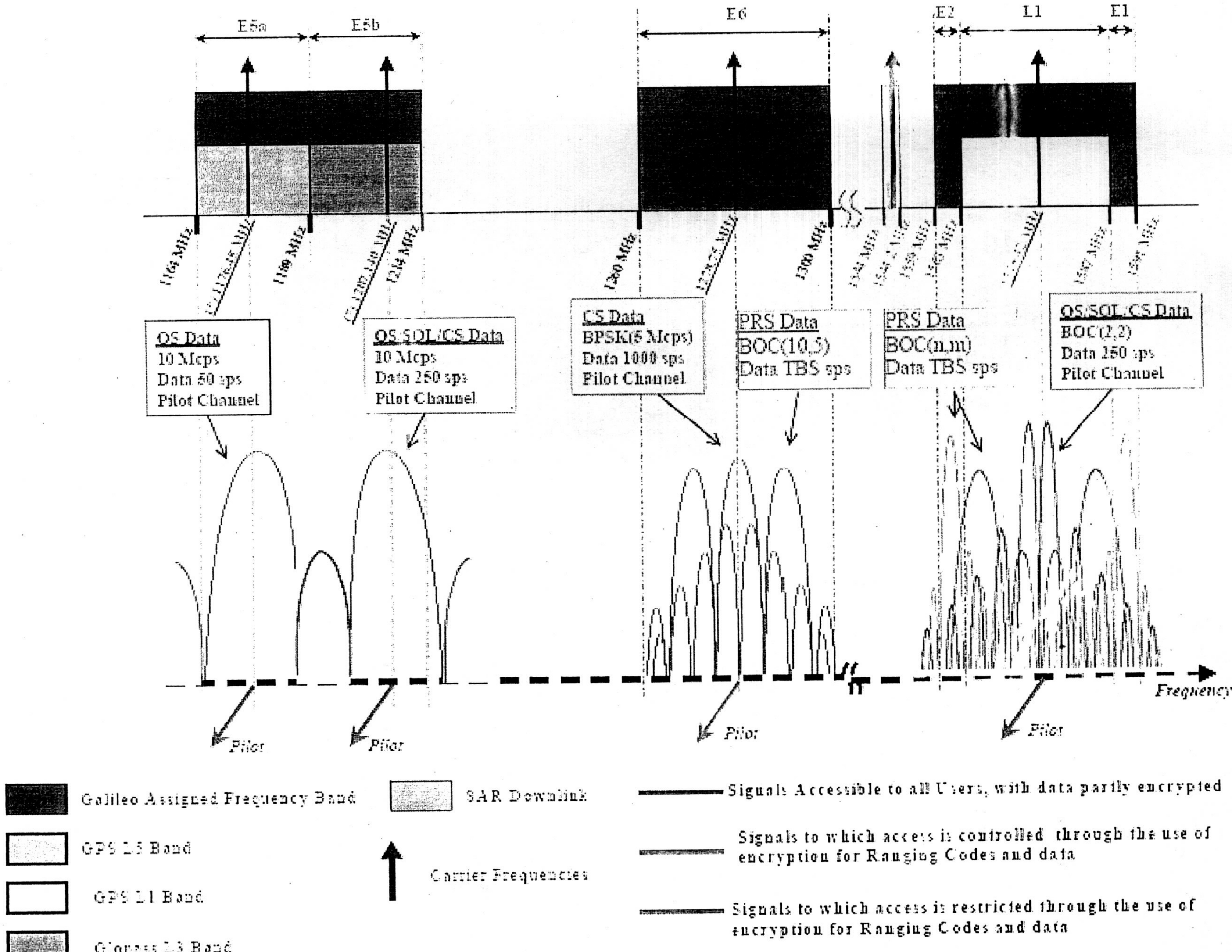


Galileo System Design

- Galileo Terrestrial Reference Frame (GTRF):
  - An independent realization of the International Terrestrial Reference System (ITRS) established by the Central Bureau of the International Earth Rotation Service (IERS).
  - GPS uses WGS84 as coordinate reference frame
  - The differences between WGS84 and the GTRF are expected to be only a few cm.
- Galileo System Time (GST):
  - Shall be a continuous coordinate time scale steered towards the International Atomic Time (TAI) with an offset of less then 33 ns.
  - Offset between GST and the GPS system time is monitored and broadcast to users, but may also be estimated in the receiver.
- Each Spacecraft will have 4 onboard clocks
  - 2 Rubidium Vapour
  - 2 Passive Hydrogen Maser

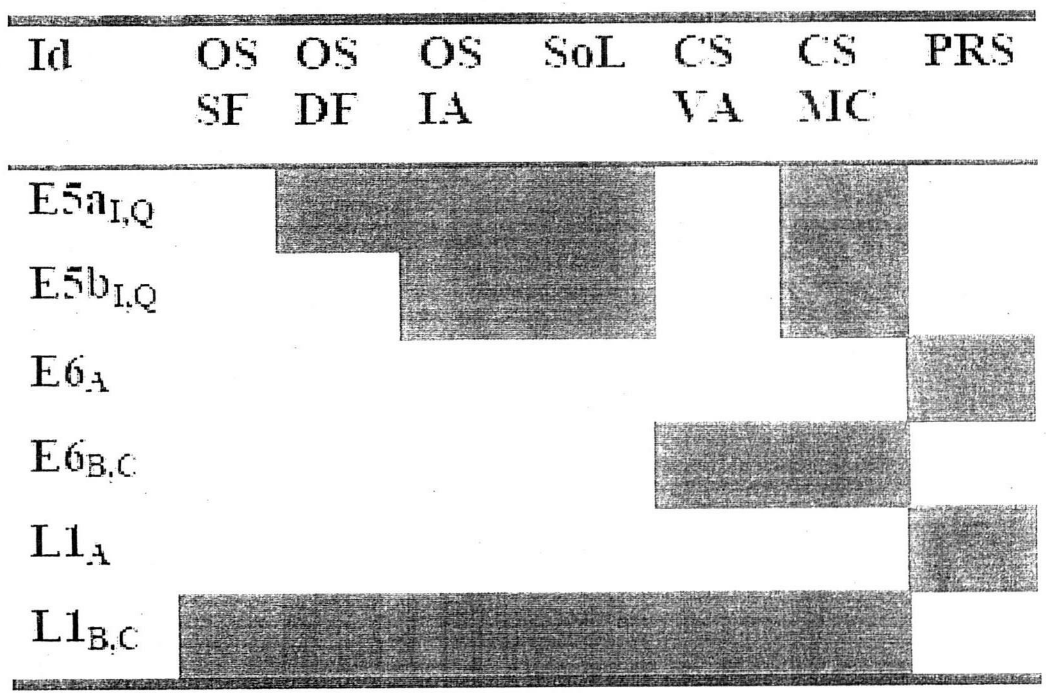
Galileo Frequency Structure





(*) In case of separate modulation of E5a and E5b signals

Galileo Services Mapped to Signals



CS	Commercial Service	DF	Dual Frequency
IA	Improved Accuracy	MC	Multiple Carrier
OS	Open Service	PRS	Public Regulated Service
SoL	Safety of Life Service	SF	Single Frequency
VA	Value Added		

GALILEO Schedule

- Development Phase
  - 2002 through 2005
  - Consolidation of Mission Requirements
  - Development of satellites and ground based components
  - In Orbit validation
  - €1.1 billion are being provided at equal shares by the European Union and by the European Space Agency
- Deployment Phase
  - 2006 through 2007
  - Construction and launch of satellites
  - Installation of complete ground segment
- Operation
  - 2008 onwards
  - gradually decreasing public funding until 2015

Interoperability

- To realize the full potential of GALILEO, other systems need to be considered:
  - Interoperability with GPS is fundamental to achieve dual-constellation availability of service
    - GPS + GALILEO >> either GPS or GALILEO
  - SBAS (WAAS/EGNOS/MSAS) and LAAS programs
  - Terrestrial Navigation Systems
  - Local Elements to enhance the service (accuracy, coverage, indoor …)
  - Communications
  - Location Based Services
- Frequency, Geodetic Reference Frame and Timescales

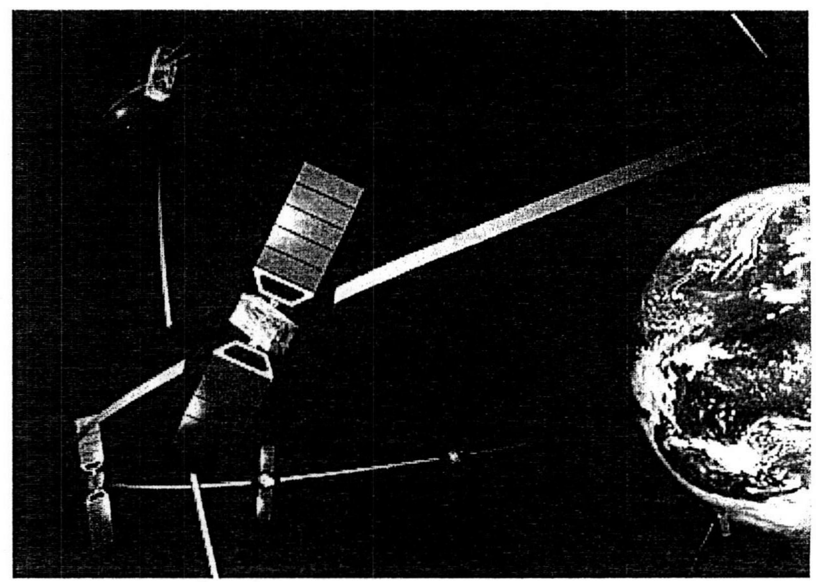
Agreement on GPS-Galileo Cooperation

- June 2004 United States and the European Union reached an agreement covering their satellite navigation services, the U.S. Global Positioning System, and Europe's planned Galileo system.
  - Ensures that Galileo's signals will not harm the navigation warfare capabilities of the United States and the North Atlantic Treaty Organization military forces
  - Calls for non-discrimination and open markets in terms of trade in civil satellite navigation-related goods and services
  - <u>Includes an agreement to establish a common civil signal at the L1 frequency</u>
- Additional availability, precision, and robustness provided by dual GPS-Galileo receivers lays the foundation for a new generation of satellite-based applications and services, promoting research, development, and investment that will benefit business, science, governments, and recreational users alike.
- Full text:
  http://www.whitehouse.gov/news/releases/2004/06/20040626-8.html

GALILEO References

Further information can be found at the following web sites:

- http://europa.eu.int/comm/dgs/energy_transport/galileo/index_en.htm
- http://www.esa.int/export/esaSA/navigation.html



Japanese GNSS Initiatives

- Japan's Multi-functional Transport Satellite (MTSAT) Satellite-based Augmentation System (MSAS)
  - Expected to provide significant benefits to GNSS users, particularly in the field of civil aviation.
- Quasi-Zenith Satellite System (QZSS),
  - Regional satellite positioning system,
  - Supplementary to and interoperable with GPS
  - Government of Japan and the private sector intend to develop and deploy QZSS according to the schedule and to work cooperatively with the United States to ensure that it benefits all GPS civil users
  - Potential to provide significantly improved regional service to positioning, timing, and navigation users in Japan and surrounding areas
- Text of Joint Statement of the United States of America and Japan on Global Positioning System Cooperation: http://www.state.gov/r/pa/prs/ps/2004/38773.htm

Time Transfer Techniques

- Satellite Navigation Systems enable a number of time transfer techniques
  - comparison of clocks at remote locations

Time Transfer Techniques

- One-way Time Transfer
  - The source, A, simply sends a time signal to the user, B, through a transmission medium
  - GPS is the most accurate worldwide one-way time transfer system
    - Stand-alone GPS receivers or GPS disciplined oscillators are available
  - A well-designed receiver system can obtain the time to better than 100 ns in a few minutes, and to about +/- 10 ns with a 24 hour average
  - In many applications a relatively inexpensive GPS timing receiver can be used in place of an atomic frequency standard
  - NIST Frequency Measurement Service

Time Transfer Techniques

Common-view Time Transfer

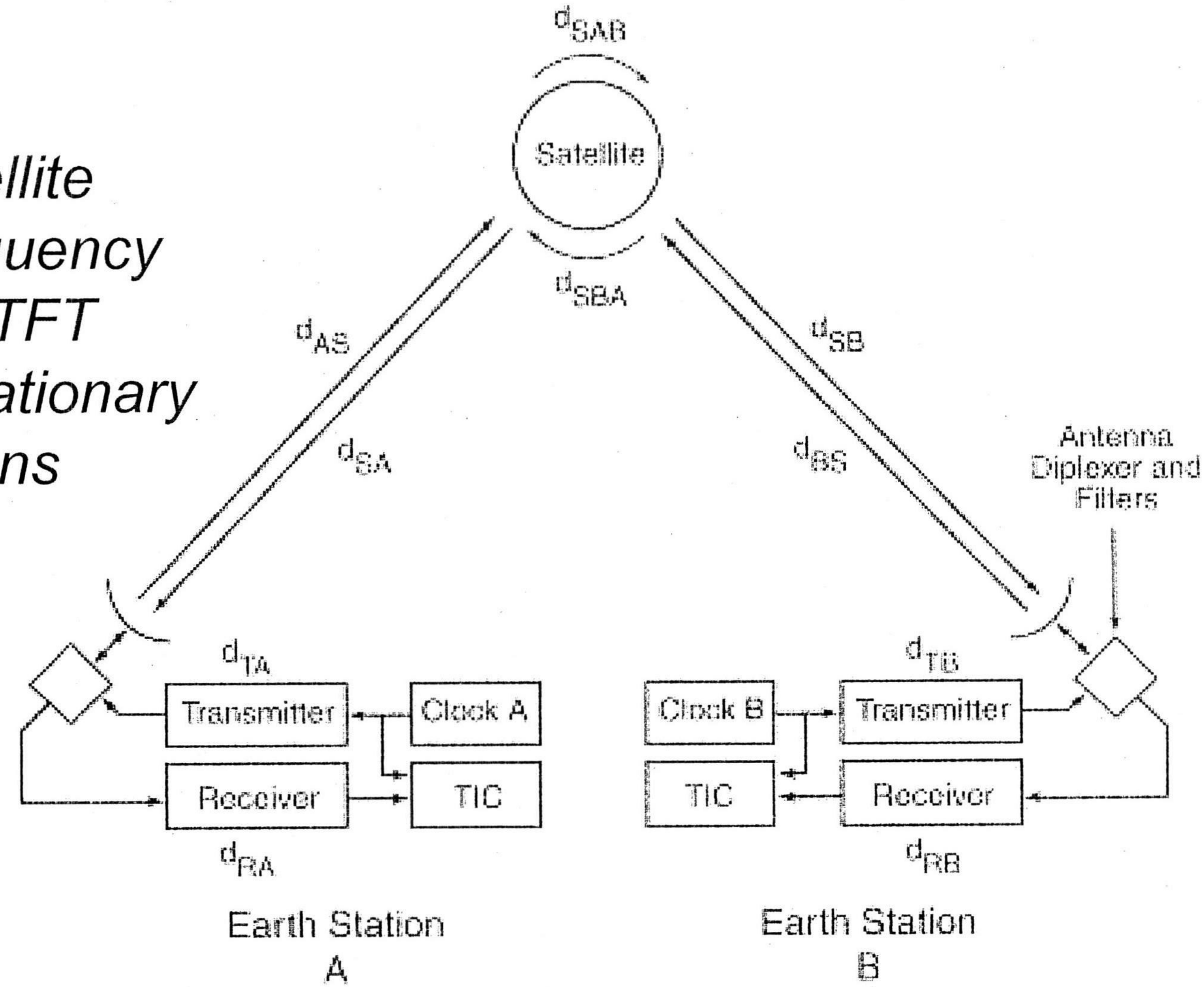
- Technique allows the direct comparison of two clocks at remote locations
- The time difference between two clocks, A and B, is determined by simultaneous observation of a third clock on a GPS satellite
- Accuracy of common-view time transfer is typically in the 1 to 10 ns range.
- NIST Global Time Service

Time Transfer Techniques

- Two-Way Satellite Time and Frequency Transfer (TWSTFT)
  - Signals travel both ways between the two clocks or oscillators that are being compared using a geostationary satellite as a relay
  - Provides stable and accurate time transfer since nearly all of the propagation delay cancels out
  - Stability of TWSTFT over a 24 hour period is better than 1 ns and has been observed to be as low as 100 picoseconds in some systems
  - Performs significantly better than Common View, but Geo satellite time is expensive

Two-Way Satellite Time and Frequencv Transfer

Two-Way Satellite Time and Frequency Transfer TWSTFT using a Geostationary Communications Satellite



Time Transfer Techniques

- **Common-View using the GPS Carrier Phase Observable**
  - GPS carrier frequency is 1000 greater than than that of the code used as the basis for other GPS-based time transfer techniques
  - The greater resolution of the carrier based measurements enables frequency comparisons with a fractional uncertainty of about 2×10^{-15} using one day of averaging
  - Before GPS carrier phase time and frequency transfer becomes routinely applied, a number of challenges remain:
    - noise in GPS reference station clocks
    - problems with undetected/unreported carrier cycle slips
    - inadequacies of current error models

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